An Introduction to

Historical Geology

ZION CANYON, UTAH

A general view through eight miles of the southern, wider and deeper part of the canyon from a point on the rim about 3000 feet above Zion Creek clearly shown at the bottom of the canyon. The rocks are nearly horizontal, non-marine sandstones—red below and light gray above—which were laid down during earlier Mesozoic time. Later the region was uplifted, much eroded, and reduced to a nearly featureless plain. At about the beginning of the present (Quaternary) period this plain, together with the whole Colorado Plateau region, began to rise thousands of feet. This rejuvenation revived stream activity and thus Zion Creek has been busily engaged in excavating the great gash known as Zion Canyon. Meantime details of the canyon walls have been sculptured by weathering processes. At the same time the Colorado River has been carving out the Grand Canyon of Arizona. (Photograph furnished by Putnam Studios, Los Angeles, California.)

An Introduction to

Historical Geology

With Special Reference to North America

By

WILLIAM J. MILLER

Professor of Geology, University of California at Los Angeles, California

Author of "An Introduction to Physical Geology, With Special Reference to North America"

"Elements of Geology, With Special Reference to North America"

FIFTH EDITION

NEW YORK

D. VAN NOSTRAND COMPANY, INC.

250 FOURTH AVENUE

First Published, *October, 1916*
Reprinted, March, 1920

Second Edition, *December, 1922*
Reprinted, February, 1925, January, 1926
February, 1926, February, 1928

Third Edition, *December, 1928*
Reprinted, January, 1929, February, 1929
January, 1930, October, 1931

Fourth Edition, *January, 1937*
Reprinted, August, 1938

Fifth Edition, *February, 1942*

PRINTED IN U. S. A.

THE PLIMPTON PRESS, NORWOOD, MASS.

PREFACE TO FIFTH EDITION

THIS revision is essentially an attempt to improve and modernize the book without in any way disturbing its basic organization or purpose.

Some twenty-five illustrations have been replaced with newer and more modern pictures. Four paleogeographic maps have been redrawn. Six structure sections have been included to illustrate the late Mesozoic and Cenozoic history of the northern Appalachian region. The text changes range from minor corrections to the important and extensive rewriting of entire sections. The most significant changes occur in the following topics which have been extensively revised and in the main rewritten: casts and molds; Cambrian history, climate, etc.; Middle and Late Ordovician history; Catskill formation; Pennsylvanian history; foreign Pennsylvanian; Paleozoic igneous rocks; foreign Triassic; Cretaceous rocks; Cretaceous history of Eastern Highland region; Cenozoic rocks; Cenozoic history of Eastern Highland region; foreign Cenozoic; driftless areas; geologic history of man; and antiquity of man in North America.

The author is grateful to various users of the book who have indicated necessary corrections and who have made valuable suggestions that have been utilized to the full.

WILLIAM J. MILLER

University of California
at Los Angeles
November, 1941

PREFACE TO FIRST EDITION

It is the author's hope that this book may find a place as a class-book dealing with the historical geology portion of a one-year course in general geology, and that it may also serve as a text for special courses in historical geology. An elementary knowledge of what is generally comprised under dynamical and structural geology is presupposed. It is assumed that a proper amount of laboratory and field work will be pursued in connection with the text.

It will be seen that more introductory space is devoted to a discussion of the broad fundamental principles of historical geology than is customary in textbooks. The experience of the author has been that careful attention to these general principles at the beginning of the subject is well repaid in satisfaction to both teacher and student when the great events of earth history are taken up in regular order.

A definite plan is strictly adhered to in the discussion of each period from the Cambrian to the Tertiary inclusive. Such definiteness of presentation, in spite of some objections which may be raised against it, should greatly aid the beginner, who must constantly compare periods and note the important changes in the evolution of both land-masses and organisms. The topical arrangements are such that any desired comparisons can be readily made. A plan of treatment, the same for both the Archeozoic and Proterozoic eras, permits a ready comparison of these two. By the very nature of the subject-matter, a somewhat more special method of discussion has been necessary for the Quaternary period.

Important features are the summaries of Paleozoic and Mesozoic history which will aid the student in fixing in mind the salient points in the history of those two great eras. It is believed that the two tabular summaries—one of Paleozoic life and the other of Mesozoic life—will be helpful. Group by group and period by period, from the Cambrian to the Cretaceous inclusive, the principal evolutionary changes in organisms are brought before the student at a glance by the use of these tables.

Students beginning the study of geology usually have either very little knowledge of biology or their study has not emphasized the classification of organisms. The evolution of organisms is a fundamental considera-

tion in the study of earth history, and the instructor finds it well-nigh necessary to present to his classes outline classifications of plants and animals accompanied by brief descriptions of the more common types. Such matter is presented in the first chapter of this book.

In certain texts, especially those portions dealing with historical geology, there is a tendency to overwhelm the student by the introduction of a multiplicity of technical terms, especially the names of fossils. The present author's idea has been to reduce such terms to a reasonable minimum required for a proper understanding of the great principles of earth history. The genus and species names accompanying illustrations are given in the interest of scientific accuracy and with no thought that these are to be remembered by the student.

Various distinctly appropriate illustrations, more or less familiar because of their appearance in other textbooks or manuals of geology, have not been abandoned merely for the sake of something new or different. Many of the illustrations, however, appear in a textbook here for the first time. Among the numerous original sources of illustrations, particular mention should be made of the publications of the United States Geological Survey, the New York State Museum, The American Museum of Natural History, and the Maryland Geological Survey.

The Macmillan Company, Henry Holt and Company, Ginn and Company, D. Appleton and Company, and John Wiley and Sons have generously allowed the use of various cuts. Careful attention has been given to the selection of only such views, fossils, diagrams, and maps as would systematically illustrate the text without overdoing this feature of the book.

The author is under particular obligation to Professor Bailey Willis of Stanford University for the use of his excellent series of paleogeographic maps of North America. These maps, together with his U. S. G. S. Professional Paper 71, have proved to be veritable storehouses from which to draw in the preparation of the manuscript of this book.

The well-known manuals and textbooks of geology, especially those by Dana, Chamberlin and Salisbury, Pirsson and Schuchert, LeConte, Scott, Norton, Blackwelder and Barrows, Geikie, Kayser, and De Lapparent, have been freely consulted, and due acknowledgment is here made for the help derived from these sources.

Among those who have read portions or all of the manuscript are the following: Dr. J. M. Clarke and Mr. C. A. Hartnagel of the New York State Museum; Professors W. B. Clark and C. K. Swartz and Mr. E. W. Berry of the Johns Hopkins University; and Dr. L. W.

Stephenson of the United States Geological Survey. Special acknowledgment is made to these men for valuable suggestions and criticisms, but the author holds himself strictly responsible for all errors the book may contain.

WILLIAM J. MILLER

Smith College,
Northampton, Mass.,
August, 1916

CONTENTS

CENOZOIC ERA

HISTORICAL GEOLOGY

CHAPTER I

SCOPE AND SIGNIFICANCE OF HISTORICAL GEOLOGY

HISTORICAL GEOLOGY deals with the records of events of earth history and with the history and evolution of plants and animals of past ages. Its object is to arrange the events of earth history in the regular order of their occurrence and to interpret their significance. The historical records are preserved in the rocks of the crust of the earth, the layers (or strata) of which have been likened to the leaves of a great book. At many places the pages of this vast "nature book" contain remarkable records and illustrations, while at others they are comparatively barren. As a result of the work of many able students of geology during the last century and a half, it has become a thoroughly established fact that our planet has a definitely recorded history running through hundreds of millions of years, and that, during the lapse of those eons, many revolutionary changes in earth features have occurred, and also that there has been a vast succession of living things which, from very early known time, have gradually evolved from simple to more and more complex forms. Here, as in all nature, ceaseless change is a cardinal principle.

In order that the reader may at the outset form a better general idea of the scope and nature of the subject, the following summary of some of the more important conclusions derived from the study of earth history is here presented.

1. *The age of the earth must be measured by hundreds of millions of years.* One great mountain range after another has been built up and then worn away by erosion. Many scores of thousands of feet (in thickness) of strata have accumulated by deposition of sediments slowly derived by the removal of many thousands of feet of materials from the lands. These and many other facts force us to the inference of a vast antiquity for the earth.

2. *The physical geography of the earth has undergone many great*

and small changes during geological time. For example, many millions of years ago, during the Ordovician period, a shallow sea spread over a large part of what is now North America. Or, the Colorado Plateau, with its Grand Canyon, was, in late geological time, a comparatively featureless surface not far above sea level.

3. *All, or nearly all, of the surface of the lithosphere has at some time, or times, been covered by sea water.* Stratified rocks of marine origin now constitute fully five-sixths of the exposed surface of the lithosphere, and it is certain that from most, at least, of the remaining surface such stratified rocks have been removed by erosion.

4. *The continents were roughly outlined in early geologic time.* This is proved by the facts that even the oldest known rocks contain much land-derived sediment of comparatively shallow water origin and that there are no deposits which show that great oceanic abysses ever extended across what are now continental areas. Much evidence points to an early development of oceanic basins and continental masses which have occupied essentially the same positions to the present time.

5. *During geologic time there has been a general tendency for the continental masses to become higher and grander.* There have been many oscillations of level, accompanied by transgressions or retrogressions of the sea, but the processes of elevation (relative to sea level) have been predominant, while, at the same time, the ocean basins have become generally deeper. The high elevation and great topographic diversity of the present-day lands seem to be unusual as compared to earlier periods of clearly recorded geological time.

6. *Organisms inhabited the earth hundreds of millions of years ago.* All but possibly the very oldest known rocks contain traces or remains of organisms.

7. *Life once started has never ceased to exist.* "It is perhaps one of the most remarkable facts established by geology that, in spite of the physical changes which we know to have occurred, the chain of life has never snapped in all the hundreds of millions of years through which its history has been traced" (W. W. Watts).

8. *Throughout the known history of the earth organisms have continuously changed.* Each epoch of earth history or series of strata has its characteristic assemblage of animals and plants. The more ancient strata contain no species like those living today, the latter being found only in rocks of comparatively (geologically) recent date. Further, "the organisms which inhabited the earth during any geological epoch were descended from organisms of preceding epochs" (W. H. Norton).

9. *The change in organisms has been progressive.* In early geological time the animals and plants were comparatively simple and low in the scale of organization and structure, and through the succeeding epochs higher and more complex types were gradually developed until the highly organized forms of the present time, culminating in man, were produced. It should be remembered, however, that not all change in organisms has been progressive, but rather only the general trend.

10. *The evolution of life has not been uniform.* "There have been periods of waxing and waning (among living things) which may be attributed to geographical, climatological, and biological influences. . . . Many factors have been of importance in quickening or checking competition, and in accelerating or retarding the evolution of life" (W. W. Watts).

11. *No species once extinct has ever reappeared.* Numerous important species have lived through many epochs of geologic time, while others have had only brief existence. In no case, however, has a species once become extinct been known to reappear.

12. *While higher and higher types have been developed during geologic time, many of the earlier and simpler types have persisted.* Thus foraminifers, which are exceedingly simple, single-celled animals, have lived in the sea from early geologic time to the present.

13. *The broader or larger biological groups of organisms have persisted longer than the smaller.* No subkingdom has ever become extinct, though species frequently have not outlived even a single geological epoch. As a rule, genera have survived longer than species, orders longer than genera, etc.

14. *The life history of the individual tends to recapitulate the evolution or history of the race.* A frog, which is a typical amphibian, shows certain fishlike characters during its embryonic development, as, for example, the presence of gills and tail. Again the modern crab, which is a crustacean, shows a gradual shortening of the tail portion during its embryonic development. The earliest known crustaceans were practically all long tailed.

CHAPTER II

FOSSILS

General Statement. Traces or remains of plants and animals preserved in the rocks are known as fossils. The term originally referred to anything dug out of the earth, whether organic or inorganic, but for many years it has been strictly applied to organisms. Paleontology, which means literally "science of ancient life," deals primarily with fossils.

Darwin thought that the stratified rocks contain only a very incomplete record of the geologic history of life. Though many thousands of species of fossils have been described from rocks of all ages except the very oldest, and more are constantly being brought to light, it must be evident that, even where conditions of fossilization were most favorable, only a small part of the life of any period is represented by its fossils. Comparatively few remains of organisms now inhabiting the earth are being deposited under conditions favorable for their preservation as fossils. So it has been throughout the long periods of earth history, though the fossils in the rocks known and unknown are a fair average of the groups of organisms to which they belong. In spite of such imperfections in the life record, it is, nevertheless, remarkable that so vast a number of fossils are embedded in the rocks, and from these we are enabled to draw many fundamental conclusions regarding the history of life on our planet.

Preservation of Fossils. 1. *Preservation of the entire organism by freezing.* Fossilization by this method is rare, though remarkable examples are afforded by extinct species of the mammoths and rhinoceroses, the bodies of which, with flesh, hide, and hair intact, have been found in frozen soils in Siberia.

2. *Preservation of only the hard parts of the organisms.* This is a very common kind of fossilization in which the soft parts have disappeared by decomposition, while the hard parts, such as bones, shells, etc., remain. Fossils of this kind are abundant in rocks of later geological

time, though original shell material is frequently found, even in very ancient rocks (Fig. 1).

3. *Preservation of carbon only (carbonization).* This is particularly true of plants where, as a result of slow chemical change or decomposition, the hydrogen and oxygen mostly disappear, leaving much of the carbon, but with the original structure often beautifully preserved.

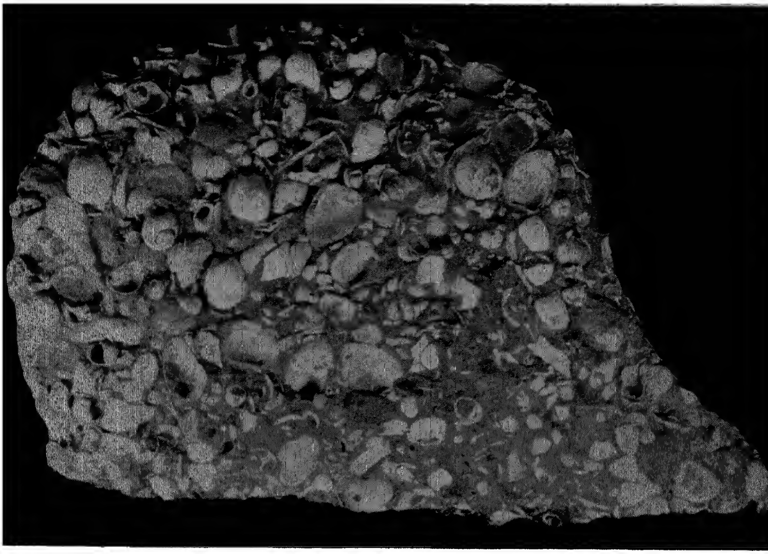


Fig. 1. A mass of well-preserved sea shells in a piece of rock of Tertiary (Oligocene) age from Oregon. Several kinds of pelecypods and gastropods are shown, × ⅔. (Photo by U. S. Grant, IV.)

Many excellent examples are furnished by the fossil plants of the great coal (Pennsylvanian) age (Fig. 2).

4. *Preservation of original form only (casts and molds).* Fossils of this class, which are very abundant, show none of the original material, but only the shape or form has been preserved. When embedding sediment or other material hardens around an entire organism or any part of it, and the organic substance then decomposes or dissolves away, a cavity only is left and this is called a mold. Fine examples are the perfectly preserved insect molds in the famous amber of the Baltic Sea region. This amber is a hardened resin, the insects having been caught in it while it was still soft and exuding from the trees millions of years ago. Since then the insect material has almost completely dried away, leaving the molds.

FIG. 2. A carbonized fossil seed fern of later Paleozoic age, × ½. (Photo by U. S. Grant, IV.)

A cast may be formed by filling a mold with some substance such as sediment or mineral matter carried by underground water. An impression of the outer surface of a shell or other organic form left in the rock is called an external mold, while the impression of the inner surface is called an internal mold (Fig. 3). Often shell and both molds are preserved, but more commonly the shell has been dissolved away. Only in rare instances have casts of wholly soft animals, or the soft parts of other animals, such as the jellyfishes and cuttlefishes, been found in ancient rocks.

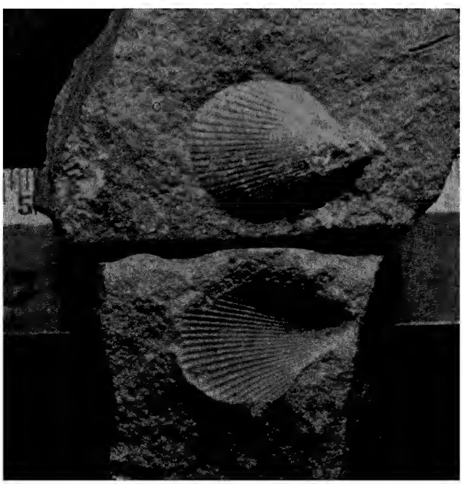


FIG. 3. Early Paleozoic rock split open to show an internal mold (above) and an external mold (below) of a sea shell, the original material of which has been dissolved away, × ½.

5. *Preservation of original form and structure (petrifaction).* Here again we have a common kind of fossilization. When a plant or hard part of an animal has been replaced, particle by particle, by mineral matter, we have what is called petrifaction. Often organic matter, such as wood, or inorganic matter, such as a carbonate-of-lime shell, have been so perfectly replaced that the original minute structures are preserved as in life (Fig. 4). Conditions favorable for the petrifaction of flesh seem never to have obtained.

6. *Preservation of tracks of animals.* Footprints of animals, made in moderately soft mud or sandy mud which soon hardens and becomes

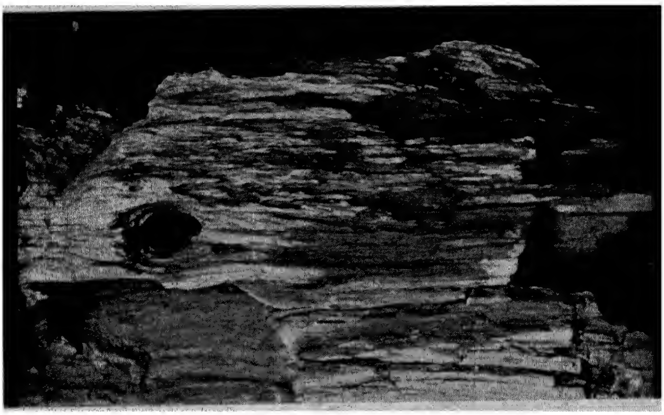


FIG. 4. A piece of petrified wood. The original material has been replaced by mineral matter (silica), × ¼.

covered with more sediment, are especially favorable for preservation. Thousands of examples of tracks of great extinct reptiles have been found in the red sandstone of the Connecticut River Valley alone (Fig. 5). Tracks or trails of clams or similar animals, and burrows of worms, are also not uncommon in the ancient rocks of the earth.

Rocks in Which Fossils Occur. 1. *Land deposits.* Old soils sometimes contain bones or other organic remains. Peat-bogs are especially favorable for the preservation of fossils, as, for example, the wealth of plants directly associated with the resulting coal seams; remains of animals, such as frogs, snakes, etc., which inhabited the swamp or bog; and the bones of other animals which wandered in and became entombed. Cave deposits often cover animal remains, many bones of extinct animals even including prehistoric man and the things he used, having been found in such deposits. Wind-blown deposits, like dune-sand, loess, and desert

deposits, may contain plant or animal remains. Interglacial deposits sometimes contain fossils, as, for example, the layers of vegetable matter with occasional bones of animals found in the interglacial deposits of the upper Mississippi Valley. Lavas rarely contain fossils, but volcanic ash

FIG 5. Footprint left by a land animal in early Mesozoic time, × ½.
(Photo by U. S. Grant, IV.)

deposited in water may be rich in organic remains, this being especially true of certain portions of the western interior of the United States.

2. *River and lake deposits.* River deposits often carry river forms themselves, or land forms which fell into the stream and became entombed in its deposits. Lakes offer very favorable conditions for fossilization. "Surrounding trees drop their leaves, flowers, and fruit upon the mud-flats, insects fall into the quiet waters, while quadrupeds are mired in mud or quick-sand and soon buried out of sight. Flooded streams bring in quantities of vegetable debris, together with the carcasses of land animals drowned by the sudden rise of the flood" (W. B. Scott).

3. *Marine deposits.* By far the largest number and variety of organic remains are found in rocks of marine origin, because on the sea bottom the conditions for their preservation have been most favorable. The distribution of fossils in strata of marine origin is, however, exceedingly irregular, ranging from those strata which are almost entirely made up of fossils to others which are nearly barren. Longshore deposits are

usually not rich in fossils, because of the grinding action of the waves, while deposits formed in the quiet waters off shore often contain vast numbers of fossils. Many conditions have produced great diversity in the distribution of marine organisms throughout known geologic time: temperature, depth of water, supply of food, degree of salinity, nature of the sea bottom, clearness of the water, etc. The oldest fossiliferous strata seem to contain practically no land forms, probably because land forms were but slightly, if at all, developed so early. In marine strata of more recent date terrestrial organisms are often found, especially in delta deposits, where such remains have been swept into the sea at the mouths of rivers.

Significance of Fossils. *General statement.* It would be difficult to overestimate the value of fossils in the study of earth history. They furnish most important evidence regarding earth chronology, ancient geographic and climatic conditions, as well as a basis for a proper understanding of the evolution, relations, and distribution of modern organisms.

"The materials with which the paleontologist must deal are the dead, unchangeable fossils, dug up from the rocks of the earth's crust, but the problems which arise from the study of these materials are far from dead, being filled with living interest and giving vitality to the whole field of historical geology. These now defunct fossils were once living, growing organisms, which were associated together in innumerable faunas, which lived in all portions of our earth, which followed one another in almost endless succession from the earliest recorded period of geological history to the present time, and which were adapted to all sorts of environmental conditions on the land and in the sea" (S. Weller).

> "These rocks, these bones, these fossil forms and shells
> Shall yet be touched with beauty and reveal
> The secrets of the book of earth to man"
>
> (Alfred Noyes).

Early views concerning fossils. As early as the sixth century B.C., Xenophanes is said to have observed fossil shells and plants in the rocks of Paros, and to have attributed their presence to incursions of sea water over the land. Herodotus, about a century later, and Eratosthenes, in the third century B.C., came to similar conclusions in regard to fossil shells in mountains far inland. Strabo, in the first century A.D., said that fossil shells far inland showed that "a great part of the continents

was once covered by water for certain periods and was then left bare again." He suggested that such marine invasions and retreats were caused by rising and sinking on the beds of the sea. None of the ancients, however, seemed to have the slightest conception of the significance of fossils as time markers in the history of the earth.

In the Middle Ages, distinguished writers held curious views regarding fossils. Thus Avicenna (980-1037) believed that fossils represented unsuccessful attempts on the part of nature to change inorganic materials into organisms within the earth by a peculiar creative force (*vis plastica*). About two centuries later, Albertus Magnus held a somewhat similar view. Leonardo da Vinci (1452-1519), the famous artist, architect, and engineer, while engaged in canal building in northern Italy, saw fossils imbedded in the rocks, and concluded that these were the remains of organisms which actually lived in sea water which spread over the region. During the seventeenth and eighteenth centuries, many correctly held that fossils were really of organic origin, but it was commonly taught that all fossils represented remains of organisms of an earlier creation which were buried in the rocks during the so-called great Deluge (Noah's Flood).

William Smith (1769-1839) of England was, however, the first to recognize the fundamental significance of fossils for determining the relative ages of stratified rocks. His announcements, based upon much careful detailed work, were made in the latter part of the eighteenth century and the early part of the nineteenth century. He has been called by the English the "Father of Historical Geology."

Earth Chronology. In any given region the best way to learn the relative ages of the stratified rocks is to determine their "order of superposition," the general assumption being that the older strata underlie the younger because the underlying sediments must have been first deposited. While this is a fundamental method, it is very limited in its application when used alone in regard to the construction of the whole earth's history. The succession of strata seen in any one locality or region represents only a small part of the earth's entire series and this, taken in connection with the fact that the lithologic character of strata of the same age frequently changes, makes it clear that "order of superposition" alone will not suffice to determine the relative ages of sedimentary rocks on a single continent or even large portion of a continent, not to mention the utter inadequacy of the method when applied to comparing the relative ages of strata of different continents.

"Order of superposition," however, when used in connection with

the fossil content of the strata, furnishes us with the method of determining earth chronology. "Life, since its introduction on the globe, has gone on advancing, diversifying, and continually rising to higher and higher planes. . . . Accepting, then, the undoubted fact of the universal change in the character of the organic beings which have successively lived upon the earth, it follows that rocks which have been formed in widely separated periods of time will contain markedly different fossils, while those which are laid down more or less contemporaneously will have similar fossils. This principle enables us to compare and correlate rocks from all the continents and, in a general way, to arrange the events of the earth's history in chronological order. . . . A geological chronology is constructed by carefully determining, first of all, the order of superposition of the stratified rocks, and next by learning the fossils characteristic of each group of strata . . . The order of succession among the fossils is determined from the order of superposition of the strata in which they occur. When that succession has been thus established, it may be employed as a general standard."[1]

The student should bear in mind that strata cannot be determined as precisely contemporaneous, because geologic time has been very long and the evolution of organisms very slow, and almost exactly similar fossils may be expected in strata showing an age difference of at least some thousands of years. Also, at any given ancient time of earth history, as now, organisms were not the same in all parts of the world, so that rocks formed at exactly the same time in different parts of the world always show certain differences in fossil content. As compared with the vast length of geologic time, however, practical contemporaneity of the strata can usually be determined.

For the determination of geologic chronology, certain organisms are more valuable than others, the best being those which have had wide geographic distribution and short geologic range. For example marine organisms, which live near the ocean surface (so-called pelagic forms) and are easily distributed over wide areas, while, at the same time, the species are extant for only a comparatively short time, are the best chronologic indicators or *index fossils*. The graptolites of the early Paleozoic era furnish excellent illustrations.

Past Physical Geography Conditions. Typical stratified rock occupying any region proves the former presence of water over that region. By the study of the fossils we can further usually tell whether the water

[1] W. B. Scott: *An Introduction to Geology*, 2nd edition, pp. 521-522 and 525.

was ocean or lake, fresh or salt, open sea or arm of the sea, deep or shallow, close to or far from land, etc. Lithologic character alone may give some idea as to the depth of water and proximity to land where a given stratum was deposited, but the presence of considerable numbers of terrestrial organisms gives important additional data. Thick limestones filled with fossil corals point to long-continued conditions of clear sea water. Tree stumps, on the other hand, with roots still in their original position, plainly prove a former land surface. By means of fossils, many land areas have been proved to have existed as effective barriers to migrations of marine organisms. Certain lands now separated by water may be shown to have been formerly connected, as was true of Alaska and Siberia, by a land connection across Bering Strait. Also the fossils found in the rocks of the Isthmus of Panama show that North and South America were there connected at a comparatively recent time in earth history.

Past Climatic Conditions. Some strata afford an idea of the climatic conditions under which they were laid down. Thus salt and gypsum beds, more or less associated with certain red sandstones or shales, indicate an arid climate at the time of their formation. But the study of fossils is much more fruitful in this connection. Certain strata in southern England contain fossil palms, gourds, crocodiles, etc., thus proving a subtropical climate for the time of their origin. Other strata, representing a later date in southern England, carry remains of Arctic animals and hence indicate a cold climate for that time. The finding of walrus remains in New Jersey and musk ox remains in Arkansas indicate a former colder climate for those regions. Again, many fossil palms, ferns, and other temperate to subtropical plants, as well as animals, clearly point to former warmer climate in those same regions.

Much strong evidence for climatic conditions over various portions of the earth during different geologic periods has been furnished by the study of true marine organisms. Certain kinds of corals live only in shallow tropical seas, and so, if in any region we find a bed of limestone rich in corals of this kind, it is to be inferred that this limestone was formed in warm, shallow sea water. Such coral limestones are known even in the interior of North America.

In deducing climatic inferences, as above explained, certain care must be exercised, because we are not justified in assuming that because a given species now lives under warm climatic conditions, every species of the same genus has lived under similar conditions. When, however, we are dealing with species still living, or in older rocks, with whole

groups of organisms pointing to certain climatic conditions, we are reasonably safe in our inferences.

Evolution of Life. It is a well established fact that, as geological time went on, both plants and animals gradually evolved and, as a rule, became more and more complex in their organization. Single-celled plants lived in Archeozoic time. Even as far along in geological time as the early Paleozoic era there were no land plants and only invertebrate animals, mostly of low-order types. By middle Paleozoic time seedless land plants and low-order seed-bearing plants, including certain types of trees, appeared. About the same time low forms of vertebrates, such as primitive fishes had been evolved. In the later Paleozoic, amphibians evolved from fishes, and reptiles from the amphibians. During Mesozoic time reptiles dominated animal life, and birds and mammals evolved from the reptiles. Late in this era the true flowering plants, representing the most complex and beautiful forms of plants, made their first appearance. During the Cenozoic era plants and animals gradually became more and more modernized. Mammals dominated the animal world, and man evolved from the primate stock at about the beginning of the present (Quaternary) period.

Relations and Distribution of Modern Organisms. It is evident that, if we are to properly understand the present-day relations and distribution of organisms, we must learn about their ancestry and history, because all modern plants and animals have descended directly from those which lived in earlier geologic epochs. In many cases existing plants or animals, notably different in structure, can be traced back to a common ancestry. Again, certain peculiarities in the distribution of some of the present-day animals are readily explained in the light of their geologic ancestry and habitats. A good example is Australia, where practically all of the present-day mammals (barring those introduced by man) are of very simple types, that is, non-placentals such as the kangaroo, spiny ant eater, etc., found only in and close to Australia, and which are clearly much more like the mammals of distinctly earlier geologic time than like typical mammals of the present day. The explanation is that Australia was separated from Eurasia before the higher (placental) mammals had been evolved, and that the very different, or probably much less severe, struggle for existence in isolated Australia has not been favorable for the evolution of placentals as was the case elsewhere.

CHAPTER III

ROCK FORMATIONS

Nature and Naming of Formations. By Stratigraphy is meant that branch of geologic science which "arranges the rocks of the earth's crust in the order of their appearance, and interprets the sequence of events of which they form the records" (A. Geikie). All stratified rocks may be subdivided into *formations* or groups of strata, each of which is marked either by a characteristic facies or assemblage of fossils, or, to greater or less extents, by similarity of lithologic (or rock) features, or by both. A rock formation is generally considered to be a mappable unit, that is its area can be delimited upon a geologic map. Subdivisions of formations are usually called members.

"The thickness of a formation or the length of time it may represent is not an essential feature. A single sequence might conceivably contain a formation thousands of feet thick and another only a few feet thick. The first might contain members each many times thicker than the entire second formation; or the second might be divided into several members and the first be undivided. . . . In naming formations it is the most general practice to adopt a geographic name derived from a "type locality" where the formation is present and sufficiently well exposed to constitute a standard of comparison. In practice it not infrequently happens that subsequent work reveals a better or more complete exposure than the type locality, and recourse is had to this as the actual standard rather than to the technical type locality. The geographic name selected is combined with either a lithologic term, if the formation is predominantly of one kind of rock, or the word "formation," if no single term is appropriate. This yields names like Dakota sandstone, Trenton limestone, Austin chalk, Genesee shale, Navarro formation, Dunkard formation, and Tejon formation" (J. B. Reeside).

Distribution of Formations. The distribution of a formation involves three considerations: (1) actual outcrops of the formation, (2) the existence of the formation where concealed under other rocks, and

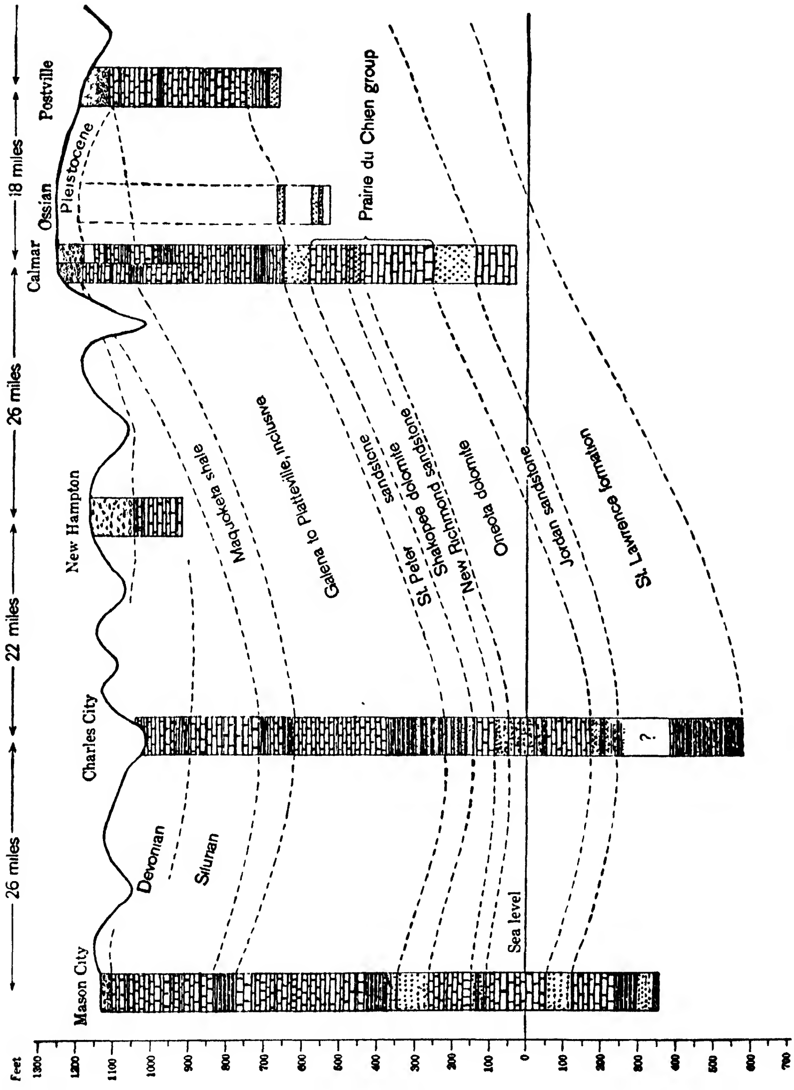


FIG. 6. Geologic section through northeastern Iowa, showing how character, thickness, and distribution of deeply buried rock formations can be determined by a comparison of well records. St. Lawrence and Jordan formations are Cambrian; Oneota to Maquoketa inclusive are Ordovician; and above these are Silurian and Devonian strata as indicated. (After W. H. Norton, U. S. Geological Survey.)

(3) where it was once present but has been removed by erosion. In the first case, in dealing with areas of outcrops of a bedrock formation, it often happens that either a small or large area comprises a single, bare exposure of the rock. More often, however, enough outcrops in an area project through a surface cover of loose, unconsolidated material, such as soil or alluvium, to make it practically certain that the whole bedrock of the area consists of a single formation. In the second case the problem is more difficult, but there are often ways of telling that a formation exists in small or large bodies concealed under other rocks as much as hundreds (or thousands) of feet below the surface. Thus an outcropping formation may be seen to extend into the earth under another formation; or the formation may be seen in one or more mining shafts; or its presence may be proved by examining the rock materials brought to the surface during the drilling of wells, many of which are thousands of feet deep, as illustrated by Figure 6.

In the third case the problem is still more difficult but, even so, surprising results may often be obtained. Thus in Figure 7 it is evident

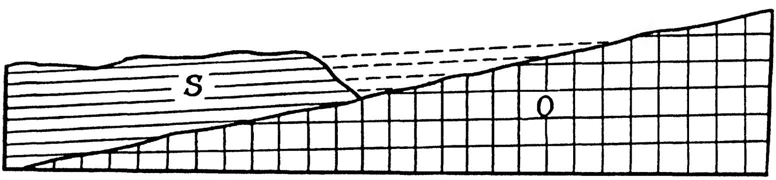


FIG. 7. Structure section to show how a pile of marine strata (S) formerly extended to the right over the old land (O) more or less as indicated by the broken lines.

that part of the pile of strata (S), (say 1000 feet thick) formerly extended to the right (say 10 miles) over the old land (O), more or less as indicated by the broken lines, but has been removed by erosion. Or scattering erosional remnants of a characteristic rock formation may prove that the formation once covered the whole area.

Geological Maps, Sections, and Symbols. A geological map shows the areal or surface distribution of rock formations or sets of formations. Such a map usually shows the areas of bedrock formations as they would appear at the surface, were there no superficial covering of loose, incoherent materials, such as soils, swamp deposits, etc. The superficial materials may be represented on a separate map, or by means of a special over-color or pattern on the bedrock map (Fig. 8).

The distribution of each formation or set of formations is repre-

sented on the map by a certain color or pattern. At the border of the map there is a so-called legend which is an explanation of the colors or patterns (Fig. 8). In the legend the various formations or sets of formations are arranged in regular order of age, with the oldest at the

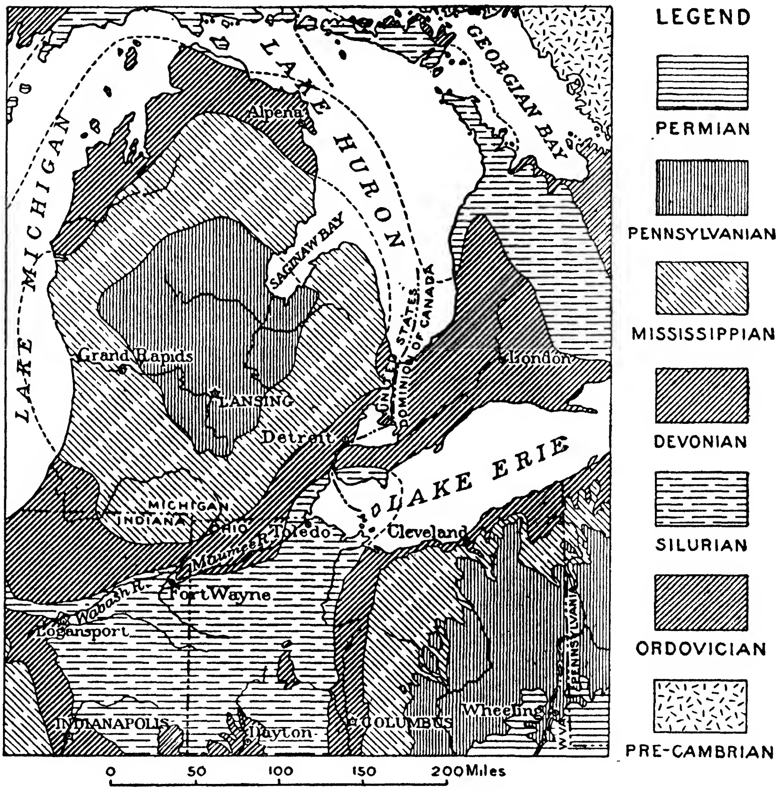


FIG. 8. Geologic map of a portion of the Great Lakes region showing the distribution of the rock systems at the surface, disregarding the soil which covers much of the bedrock. (After U. S. Geological Survey.)

bottom. In many cases the surface distribution of formations, as shown on a geological map, gives no real indication of the actual extent of the formations in the crust of the earth. Extensive formations which have been notably tilted or folded may appear as only narrow belts at the surface (Fig. 9).

"In cliffs, canyons, shafts, and other natural and artificial cuttings the relations of the different beds to one another may be seen. Any cut-

ting that exhibits those relations is called a section, and the same term is applied to a diagram representing the relations. The arrangement of the rocks in the earth is the earth's structure, and a section exhibiting this arrangement is called a structure section. Knowing the manner of formation of rocks, and having traced out the relations among the beds on

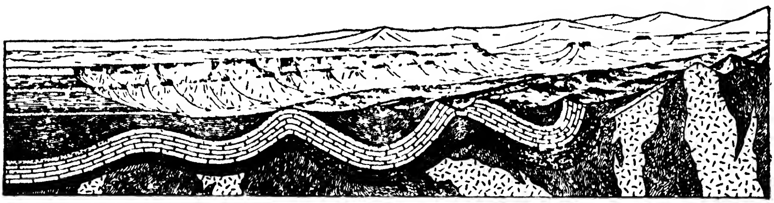


FIG. 9. Sketch map showing a structure section at the front, and a landscape beyond. (After U. S. Geological Survey.)

the surface, the geologist can infer their relative positions after they pass beneath the surface, and he can draw sections representing the structure to a considerable depth. Such a section is illustrated in Figure 9. The

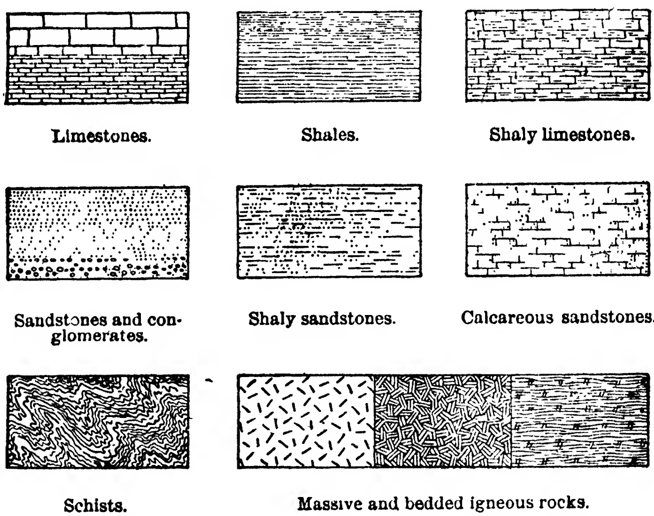


FIG. 10. Symbols used to represent common kinds of rocks. (After U. S. Geological Survey.)

kinds of rock are indicated by appropriate patterns of lines, dots, and dashes. These patterns admit of much variation, but those shown in Figure 10 are used to represent the commoner kinds of rock." (U. S. Geological Survey.)

A brief history of the main geological events recorded in their order of occurrence in the structure section (Fig. 9) is as follows: Deposition of the original material of the schist, metamorphism and folding of the schist, intrusion of the igneous masses, profound erosion, deposition of shale and limestone upon the eroded surface, folding of the rocks especially well shown by the shale and limestone, a second interval of erosion, deposition of shale and sandstone upon the second eroded surface, uplift without deformation, and erosion producing the present-day landscape.

A columnar section contains a concise description of the formations which occur in a large or small area as they would appear if all piled up in one locality in order of age and in undisturbed condition. Such a section involves a columnar diagram which shows the kinds and order of superposition of the formations, and data on either side of the diagram opposite each formation giving its thickness, description, age, and usually its name (e.g. Fig. 93). Original structures, such as unconformities, are often shown, but subsequent structures, such as folds and faults, are seldom represented.

Correlation of Formations. By correlation of formations is meant the determination of the age equivalence, or practical equivalence, of rock groups or formations in various parts of the earth. Exact contemporaneity for widely separated districts cannot be expected as above explained in chapter II. In general the criteria of correlation may be divided into two classes, namely, geological (physical) and paleontological (biological).

I. Geological (physical) criteria. In many cases formations carry no fossils or very few, and it is then necessary to seek means of correlation without their aid. None of the geological (physical) methods can, however, be applied over wide areas such as opposite sides of a continent, or different continents. For such wide correlations, criteria derived from a study of fossils only can be used. Various physical factors used in correlation of formations are as follows:

1. *Continuity of deposit.* If, as shown in the accompanying diagram (Fig. 11), continuity can be traced from A to B, it is quite certain that the rock masses at A and B are of the same, or very nearly the same, age. There is probably no more important means of correlation used by the geologist except over wide areas.

2. *Similarity of materials.* Rock formations not actually continuous, though not too widely separated, are often correlated by noting similarity

or identity of lithologic character, especially if there are any locally peculiar features. Earlier geologists were inclined to overwork this method of correlation by applying it over areas of too great extent, in some cases even suggesting identity of age of deposits on opposite sides of the ocean by this means. The danger of such application is apparent

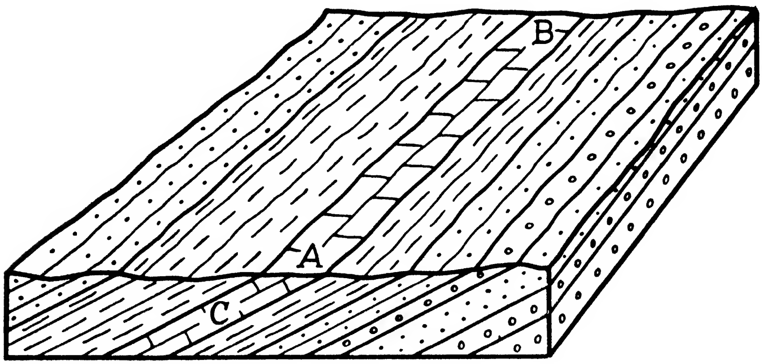


FIG. 11. A block diagram of part of the earth's crust with tilted strata. It illustrates correlation of formations by continuity of deposit from A to B as explained in the text. It also shows surface distribution of various formations and subsurface distribution in the structure sections at front and right sides.

when we realize that, for example, a sandstone of very early (Cambrian) age may be in physical appearance exactly like sandstone of much later (Tertiary) age.

3. *Similarity of sequence.* A succession of strata in two places like A and B (Fig. 12), and not continuous at the surface, may be correlated on the basis of similarity of sequence, particularly when each formation at one place (A) shows little or no difference in lithologic character or thickness as compared with each formation at the other place (B).

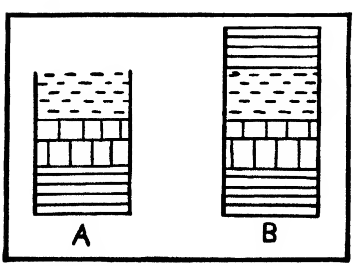


FIG. 12. Columnar sections to illustrate correlation of rock formations by similarity of sequence.

4. *Similarity of degree of change, or structural relations.* By finding similarly changed or metamorphosed rocks in the same vicinity, they may thus be correlated. For instance, in the accompanying diagram (Fig. 13) it is evident that the rocks of group A are older than those of group B,

because A are folded and B are not; and B are older than C because B were tilted by regional diastrophism before C were deposited. Outcrops over limited areas at least can thus be placed in one of these three groups. By way of illustration, the (pre-Paleozoic) rocks of the Highlands of the Hudson in southeastern New York are highly metamorphosed and folded, with indurated, folded (Ordovician) strata resting upon their north side, and indurated, non-folded, and slightly tilted (Triassic) strata coming against them on the south side. Each of these groups of rocks represents a distinctly different geologic age. This

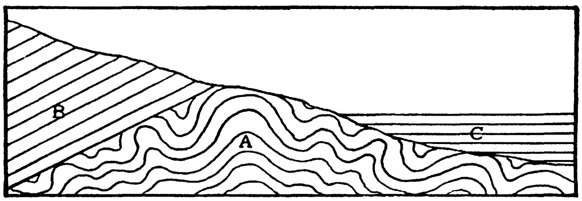


FIG. 13. Structure section to illustrate correlation of rock formations by degree of change or structure in a local region. See accompanying explanation.

method cannot be used over wide areas such as different parts of a continent, because, for instance, certain strata (Cretaceous) in the eastern part of the United States may be unconsolidated and horizontal, while rocks of the same age are highly folded in the western United States.

5. *Study of adjacent lands.* Examination of the materials of the Atlantic Coastal Plain clearly shows, by their nature, that they have been largely derived from the rocks of the Piedmont Plateau and Appalachian Mountains, and hence these Coastal Plain materials are the younger. Also the peneplain character of the surface of the Piedmont Plateau proves the greater age of this region because the peneplain was being produced by wearing off the very materials which were deposited in the adjacent ocean to produce what are now called the Coastal Plain deposits.

6. *By diastrophism.* According to T. C. Chamberlin, the great deformations of the earth's crust have been of periodic occurrence. Each great movement has "tended toward the rejuvenation of the continents and toward the firmer establishment of the great (oceanic) basins." Between any two great diastrophic movements there has been a time of quiescence when the base-leveling processes have more or less lowered the continents. Such "base-leveling of the land means contemporaneous filling of the sea basins by transferred matter" with resultant encroach-

ment of the sea over the land "essentially contemporaneous the world over," which in turn implies "a homologous series of deposits the world over." Thus the times of great diastrophism (recognized by profound, widespread unconformities) should form the basis for separating and correlating at least the larger groups of strata in the earth's crust. In the light of recent studies, this generalization needs more or less modification.

II. Paleontological (biological) criteria. The significance of fossils in the determination of geological chronology has already been discussed, but it should here be repeated for emphasis that "order of superposition" of the strata, studied in connection with their fossil content, furnishes the general standard for building up a geological chronology, and affords the best basis for the correlation of formations. In fact, for correlation of formations in distant portions of a continent, or different continents, paleontological criteria alone are entirely satisfactory. Important paleontological criteria are as follows:

1. *Identity of species.* This is an extremely important method of correlation, especially when species with wide geographic distribution and short geologic range are employed. It is not wise to depend upon a single species for the correlation of far distant formations, because then the time necessary for the migration of the species must be considered. This seldom gives trouble because the geologist usually deals with a number of rapid-moving species. In a restricted area, where formations are to be correlated, the same organisms may have continued for a long time, but nearly always some peculiar species furnishes the clew.

2. *Aggregations of forms.* When groups of strata in different areas carry similar aggregations of similar forms, the groups of strata may be safely correlated. Even though a small percentage of the species vary, the method still holds because such variations are to be expected on account of migratory and geographic conditions.

3. *Stage in the evolution of organisms.* Since there has been a gradual development of life with increasing complexity throughout geologic time, the stage of development or evolution shown by the fossils in a group of strata will serve as a basis for general correlation at least. Each era, or even period, shows a characteristic stage of evolution of forms.

4. *Percentage of living species.* This applies only to rock formations of later geologic time, because the older rocks contain no species like those now living. The percentage of living species becomes greater and greater as the present time is approached, and on this basis Lyell subdivided a late period (Tertiary) into three epochs.

In any correlation problem the geologist strives to use as many of the above criteria as possible, the certainty of the correlation being more firmly established when several geological and paleontological criteria are used together.

Unconformities. Thus far our discussion has been based largely upon the assumption of conformable strata, but many times the succession of strata (so-called "section") under study shows one or more unconformities. An unconformity represents an interruption in the stratigraphic succession. It is nearly always an erosional surface separating two sets of rocks. Rarely, however, it may represent a time of almost complete non-deposition of strata in a submerged area.

In a typical case, after a pile of strata has accumulated to a certain depth in a given region, an emergence, usually due to diastrophism, may take place, resulting in a removal of part of the pile of strata by erosion. The emergence generally involves uplift, often accompanied by folding

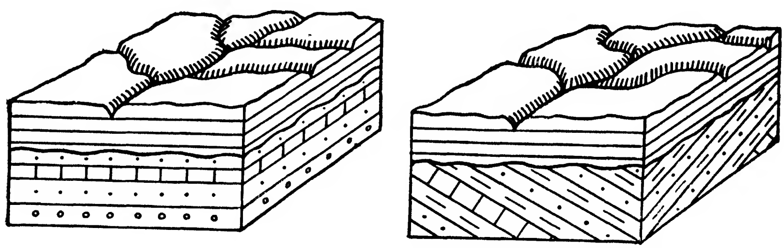


FIG. 14. Block diagrams to illustrate a disconformity (on the left) and a non-conformity (on the right). The heavy irregular line marks the erosional surface or unconformity.

or tilting, but the pile may remain horizontal or nearly so. Then, due to submergence, newer strata may be deposited upon the eroded surface of the remaining older rocks (Fig. 14). The surface of erosion separating the newer from the older set of rocks is called an unconformity.

It should not be presumed that unconformities exist only in stratified series. Thus, among other cases, there may be an unconformity between either igneous or metamorphic rocks and ordinary strata.

In the case of an obvious unconformity, where the upper strata lie upon the eroded surface of tilted or folded strata, or of igneous or metamorphic rocks, the term "non-conformity" is applied (Fig. 14). If, however, two sets of strata, separated by an erosional surface, have their stratification practically parallel, the term "disconformity" is applied.

From the above considerations, it is evident that an unconformity signifies a gap or break in the geological record at the locality concerned, that is an absence of both the strata and the fossil record representing a greater or less length of geological time. The missing records for a given region can, however, generally be found by going to some other locality where deposition of sediments was not interrupted at the time when the unconformity was being produced.

Without the aid of fossils, in the ordinary case of unconformity, we could tell that the land emerged above water, was eroded, and again submerged, but we could not tell how much time was involved (Fig. 14). But by noting the index fossils in the youngest strata just below the eroded surface, and in the oldest strata just above it, we could tell what epochs or periods the unconformity represents by a comparison with the standard geologic divisions of the world (see table near the close of this chapter).

Because the fossils immediately above and below the line of a profound unconformity show such marked differences, the earlier geologists were misled into thinking that each great unconformity signified an awful catastrophe (physical and organic) which devastated the earth and destroyed all organisms, after which came a period of tranquillity when a new set of organisms was created. This has been called the doctrine of catastrophism. In opposition to this view Sir C. Lyell promulgated the doctrine of uniformitarianism which holds that the evolution of the earth and its inhabitants has progressed practically uniformly, and that missing records in one place are to be found in other places. Today Lyell's view is generally accepted with the modification that times of comparatively more rapid earth disturbance, and probably changes in organisms, have occurred.

CHAPTER IV

RELATIONS OF CONTINENTS AND OCEAN BASINS

Persistence of Continents and Ocean Basins. There is strong evidence that the present-day continents and ocean basins have, in a general way, persisted since early Paleozoic time, and probably much longer than that. Some reasons for believing that ocean basins and continents have never changed places are: (1) Earth material under the oceans is heavier than that under the continents. Also, ocean basins and continents are in almost perfect equilibrium. These facts have been proved by gravity tests, using the pendulum method, in many places. To change this density equilibrium enough to permit an ocean basin, such as the deep Atlantic, to rise as a continent would necessitate a reversal of specific gravity between a continental and an oceanic segment of the earth. There is no evidence that such a change ever occurred, and it is almost impossible to imagine how it could be brought about. (2) Deep-sea deposits, similar to those now accumulating in the abysses of the ocean, are entirely unknown well within the present-day continents. Such deposits of very limited extent do occur on a few islands of the Mediterranean, East Indies, and West Indies, but these are all on continental margins or islands in regions of unusual diastrophic activity where great uplifts have occurred during Cenozoic time. It is evident, then, that a continental area like North America was never the site of a deep sea. It is true, nevertheless, that marine strata of various ages are common and widespread on the continents, but these plainly show by their nature and origin that they were laid down in shallow or very shallow seas which overspread parts of the continents from time to time.

Various more or less important changes in the general outlines of continents and ocean basins have taken place. The ocean basins seem to have been deepening and widening, while the continents have been getting narrower and higher. "There were, in all probability, no great depths in the oceans, that is, depths to which the light could not penetrate sufficiently for plant growth, earlier than the Triassic, for the animals now living at these depths are most closely related to those which evolved in shallow waters during the Mesozoic, and less closely to those of the

Cenozoic. All surviving Paleozoic water-dwelling genera are today confined to shallow waters" (H. W. Shimer). Among various examples of widening of ocean basins, mention may be made of Japan and Madagascar, each of which is separated from the mainland by sunken areas occupied by sea water hundreds of miles wide, and the islands off southern California much closer to the mainland. All three of these areas were connected with the mainland in later geological time as indicated by the similarity of animal life, and all of them represent sinking of parts of continental masses into the ocean basins. Facts presented in subsequent pages of this book show that, for hundreds of millions of years, there has been a tendency for the continents to become higher, though by no means at any uniform rate. Thus the present average

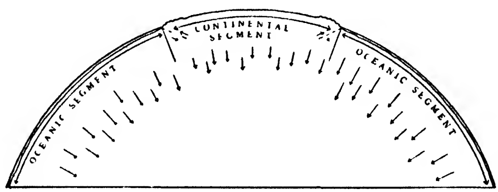


FIG. 15. Diagram to illustrate deformation of a continent. Arrows pointing toward center of earth indicate general condensation. Long arrows represent tangential compressive stress. All segments sink, but the continent is wedged up somewhat relative to the oceanic segments. Dash lines represent shear under the continents. Vertical lines represent relations of segments before diastrophism. (After T. C. Chamberlin.)

altitude of North America is about 2000 feet, but during most of Paleozoic time it was less than 1000 feet. During Mesozoic time the average altitude of the continent was nearer that of the present time.

Irrespective of any theory that we may hold in regard to the origin of the earth, there are good reasons for believing that our planet has been, for long geological ages, a heterogeneous shrinking body. Among the evidences are the following: profound folding of belts of the earth's crust (orogeny); broad relative uplifts and warpings of the earth's crust (epeirogeny); and general more or less periodic sinking of oceanic areas, all of which have occurred at various times and in many places.

The accompanying diagram (Fig. 15) gives a good idea of T. C. Chamberlin's conception of oceanic and continental segments in relation to earth shrinkage and lateral compression.

Transgressions and Retrogressions of the Sea. During our study of the clearly recorded portion of the earth's history we shall find posi-

tive evidence of repeated transgressions and retrogressions of marine waters over various portions of what are now the continental areas. It is believed that such continental seas were comparatively shallow, that is rarely as much as 1000 feet deep. Since subsidences or elevations of the lands are not the only known causes of sea transgressions and retrogressions, we shall, in the following pages, refer to submergences and emergences of the lands unless there is good evidence for more specific statement in any case.

Submergence may be caused either by (1) sinking of the land; (2) rise of the sea; or (3) both together. "Both the lowering of the land and the rise of the sea may be due to gradation, to diastrophism, or to the two combined. Gradation is perpetual and inevitable where land and sea exist. . . . It has been computed that if the earth, in its present condition, were to remain without deformation long enough for the continents to be base-leveled, the deposition of the sediments thus derived in the sea would raise the sea-level about 650 feet. This would submerge a large part of the base-leveled land. . . . Base-leveling implies a nearly undisturbed attitude of the land and sea, and hence in itself favors the view that no great deformation affected the continent while it was going on."[1] Much submergence of lowlands would take place long before such widespread base-leveling had been accomplished. Sinking of the land (see below) would of course cause submergence, but whether submergence of the land, in any given case, has been due only or largely to sinking or gradation or to both is at present often difficult or impossible to determine, though it is quite certain that both processes have often been operative.

Emergence may be caused either by (1) rise of the land; (2) lowering of the sea; or (3) both combined. Except rather locally as in the cases of mountain-making (orogenic) movements, it seems doubtful if there is any good evidence for very considerable actual uplifts of extensive land areas thus causing great sea retrogressions. On the other hand, the earth is certainly a contracting body with its whole surface approaching nearer and nearer to its centre. It appears that "the rigidity of the earth may be such that its outer parts are able to withstand for a time the strain set up by contraction. As the strain accumulates, it ultimately overcomes the resistance, and the outer part of the earth yields. If the yielding results in the sinking of the ocean basin, the surface of the water is drawn down, and the surrounding lands seem to rise, unless they sink as much as the surface of the sea does at the same time. The lowering

[1] Chamberlin and Salisbury: *College Geology*, p. 479.

of the sea surface, because of the sinking of the sea-bottom, is probably the most fundamental single cause of the apparent rise of the land. The periodic emergences of the continents, alternating with periodic submergences in the course of geological history, are perhaps to be thus explained. Periodic submergences, on the other hand, might be explained by the sinking of the continental segments of the earth, or by such sinking combined with the processes already referred to which cause the rise of the sea." [1]

The idea of periodic or rhythmic recurrence of the greater diastrophic forces and events has become an important tenet of historical geology. It seems to have been a rule that times of especially great activity—often very widespread—have alternated with times of quiescence. This is strikingly illustrated, as we shall learn, by the advances and retreats of marine waters over large parts of North America during the Paleozoic era. The most profound times of diastrophism, causing widespread emergence of land or great mountain-making, mark the close of the geologic eras while lesser times of activity usually mark the close of the periods.

Significance of Geosynclines. A relatively long, large subsiding downwarp or trough, on a continent, in which sediments accumulate to great depth during a long geological time is called a geosyncline. The sediments are generally of marine origin. In order of magnitude, geosynclines usually range from 100 to several hundred miles in width, and from several hundred to several thousand miles in length.

A typical geosyncline generally lasts through at least several geological periods, and sediments pile up in it to a depth of many thousands of feet—commonly 20,000 to 50,000 feet. Since the strata are of shallow-water origin as proved by coarseness of grain of much of the material, character of the fossils; ripple marks, mud cracks, etc., and since they pile up to such a great thickness, it is obvious that the floor upon which the sediments accumulate must subside more or less gradually during the process of deposition, and at about the rate of deposition.

The finest large-scale examples of geosynclines in the history of North America were the Cordilleran trough extending 3000 miles across the western part of the continent, and the Appalachian trough extending 2500 miles across the eastern part of the continent as shown by Figure 145. Each of these lasted through most of Paleozoic time.

A remarkable fact is that, after long subsidence, a typical geosynclinal basin loaded with sediment is subjected to pressure at right angles to the

[1] R. D. Salisbury: *Physiography, Advanced Course*, pp. 401-402.

axis of the trough, and folded and raised into a mountain range. This is because such a geosyncline marks a zone of exceptional weakness in the crust of the earth.

Paleogeographic Maps. Paleogeography literally means "ancient geography" and deals with the geographic conditions of the earth during geologic time. In making a paleogeographic map to represent North America at a given time in its history, the attempt is made to show the relations of lands and waters, sometimes with distinctions between areas of marine and of continental deposition, location of highlands, etc. Until the present century there were only crude attempts at making such maps for North America, for the knowledge of the continent was not sufficient to form a reasonable basis upon which to work. Within the last thirty-five years, however, several sets of paleogeographic maps, notably those by Charles Schuchert, have been prepared. The maps used in this text are based upon data from various sources. A good example of a paleogeographic map is shown by Figure 42.

To make a paleogeographic map showing the relations of sea and land during a given geological age, sea water should be represented as covering areas (1) where marine strata of that age are known to outcrop, (2) where such strata are known to exist under cover of other formations, and (3) where such strata once existed but have been removed by erosion. From a study of the nature and distribution of the sediments, a good deal may often be learned in regard to the topography of the land areas of the age. Thus a nearly pure limestone formation indicates that land was a long distance away or was too low to furnish a very notable amount of clastic sediments. Thick deposits of coarse sediment show near-by high land with swift streams supplying the sediments. Large amounts of shales and fine-grained sandstones strongly indicate rivers which flowed long distances across large land areas.

It should be borne in mind that such paleogeographic maps are generalized and rather tentative as regards many details—generalized because each map represents a considerable time period so that certain more local geographic changes during the period are not indicated, and tentative because of lack of knowledge concerning many areas and lack of certainty in the correlation of formations in certain other areas. With progress in knowledge of the strata, less generalized and more accurate maps will be made. Nevertheless the series of maps used in this text will serve to give the beginner a very good idea of the broader features in the geographic development of our continent.

CHAPTER V

GEOLOGIC TIME

Classification of Geologic Time. We have already shown how, by employing the law of superposition of the strata together with the law of included fossils, the rock formations of various parts of the earth may be correlated and built up according to their natural order of age into a standard for comparison or a geologic column. The subdivisions of the geologic column represent the times when the successive rock formations were deposited. Different names have, from time to time, been assigned to these divisions, and these names are in more or less general use.

For a long time the subdivisions of the geologic column were made almost solely on the basis of marked differences in fossils, but it is now recognized that such differences were, in no small degree, caused by corresponding changes in the environment in which the organisms lived, or, in other words, by changes in the climate, the topography, the relations of land and sea, etc. So we now try to divide the geologic record at the points where the revolutionary physical changes are indicated, and to make corresponding divisions of geologic time itself. Thus there are two kinds of divisions—one for the rocks themselves, and the other for the time represented by the rocks.

The following time and rock scales have been adopted by the International Geological Congress. Following these scales, there is presented the table of main geological divisions as now recognized in North America.

Time Scale	*Rock Scale*
Era	Group
Period	System
Epoch	Series
Age	Formation

The names of eras follow a definite plan depending upon the great life stages. Thus Archeozoic means literally "primitive or beginning life"; Proterozoic means "earlier or less primitive life"; Paleozoic means

MAIN DIVISIONS AND EVENTS OF GEOLOGICAL TIME

ERAS	PERIODS	PHYSICAL EVENTS IN NORTH AMERICA	CHARACTERISTIC LIFE			YEARS AGO
CENOZOIC	Quaternary	Widespread rejuvenation and erosion Periodic extensive glaciations Coast Range revolution	Age of mammals	Age of angiosperms	Rise of man Modern plants and animals	0 to 1,000,000
	Tertiary	Many physical disturbances Great vulcanism in the west Marine conditions over continental margins only			Rise of highest mammals except man Great development of highest plants	1,000,000 to 50,000,000
MESOZOIC	Cretaceous	Rocky Mountain revolution A great western-interior sea Important chalk deposits	Age of reptiles		Modernized angiosperms and insects abundant Foraminifers profuse Extinction of dinosaurs, flying reptiles, and ammonites	50,000,000 to 200,000,000
	Jurassic	Sierra Nevada revolution Widespread erosion Some red beds in western-interior Marine conditions on west coast		Age of gymnosperms	First (reptilian) birds First of highest forms of insects First (primitive) angiosperms Culmination of ammonites	
	Triassic	Widespread arid climate with great deposits of red beds Marine conditions and much vulcanism on west coast			Earliest dinosaurs, flying reptiles, marine reptiles, and primitive mammals Cycads and conifers common Modern corals common Earliest ammonites	
PALEOZOIC	Permian	Appalachian revolution Some red beds in western-interior Great salt beds in western-interior Extensive sea in the west	Age of amphibians		Rise of primitive reptiles Earliest cycads and conifers Extinction of trilobites Amphibians common and varied First modern corals	200,000,000 to 500,000,000
	Pennsylvanian	Ouachita revolution Warm, humid climate with a profusion of coal-making plants Extensive sea in the west		Age of spore plants	Earliest known insects Culmination of amphibians Spore plants abundant and varied	
	Mississippian	Ouachita disturbance Two large marine transgressions			Rise of amphibians Culmination of crinoids	
	Devonian	Acadian revolution One great marine transgression	Age of fishes		First known seed plants and forests Great variety of boneless fishes First evidence of amphibians Culmination of brachiopods	
	Silurian	Three great marine transgressions Great limestone deposits Great salt beds in the east	Age of invertebrates		Earliest known land animals Primitive land plants Rise of fishes Brachiopods, cephalopods, trilobites, crinoids, and corals abundant	
	Ordovician	Taconic revolution Three great marine transgressions Very extensive limestone deposits			Earliest known vertebrates Graptolites, corals, crinoids, bryozoans, brachiopods, cephalopods, and trilobites abundant Oldest recognizable, primitive land plants	
	Cambrian	Green Mountains disturbance Two great marine transgressions Extensive deposits of clastic sediments		Age of thallophytes	All subkingdoms of invertebrate animals represented Brachiopods and trilobites common Primitive land-plant spores? Water-dwelling thallophytes	
PROTEROZOIC	Keweenawan	Extensive glaciation Killarney revolution Great vulcanism in the Lake Superior region	Rise of invertebrates		Primitive water-dwelling plants and animals	500,000,000 to 1,000,000,000
	Huronian	Great iron-ore deposits Earliest known glaciation Great sedimentary deposits				
ARCHEOZOIC	Timiskaming	Algoman revolution with great intrusions of granite Extensive sedimentary deposits (all metamorphosed)	No animal fossils found		Oldest known life (mostly indirect evidence)	1,000,000,000 to 1,800,000,000
	Keewatin	Laurentian revolution Earliest known sedimentary and volcanic rocks (all metamorphosed)				

"ancient life"; Mesozoic means "intermediate life"; and Cenozoic means "recent life." The period names do not follow such a definite plan of nomenclature, various ideas being represented. These names will be explained when the different periods are taken up for discussion.

Length of Geologic Time. How old are the Archeozoic rocks? If we attempt to answer this question in terms of years we encounter real difficulties, there being no definitely established exact standard for such measurement or comparison. In any case the time is utterly inconceivable to us, the important thing to bear in mind being that the great events of well-known earth-history which have transpired since the formation of the oldest known Archeozoic rocks have required a lapse of at least hundreds of millions of years. Among such events have been the long, slow, generally progressive evolution of life; the enormous accumulations of sediments at many times and places; the repeated advances and retreats of the sea over many parts of the continents; the building up and wearing away of mountain ranges at many times and places; as well as various other profound changes which have affected the face of the earth. On the basis of such geological happenings, an exceedingly conservative minimum estimate of the age of the Archeozoic rocks is 500,000,000 years.

Measurements of time on the basis of radioactivity run much higher. In radioactivity a chemical element of higher atomic weight is transformed into one of lower weight. Thus uranium changes through successive stages of radium into a certain type of lead. The rate of this change is said to be rather accurately known, so that the determination of the amount of the special type of lead in minerals containing uranium affords a means of ascertaining at least approximately the time when the transformation started. Based upon this principle, an age of considerably more than a billion years has been assigned to the Archeozoic rocks; the Paleozoic era opened more than 500,000,000 years ago; the Mesozoic era nearly 200,000,000 years ago; and the Cenozoic era at least 50,000,000 years ago.

Comparison of Human and Geologic History. One of the most striking differences between human and geologic history is the extreme brevity of the one as compared with the vast time represented by the other. Human history is to be measured by some thousands of years, while geologic history must be measured by at least scores of millions of years. A recent event, geologically speaking, like that of the building of the Coast Range Mountains, or the carving out of a tremendous canyon

like the Grand Canyon of the Colorado in Arizona, required some hundreds of thousands, if not a few millions, of years. Human history is roughly divided into certain ages according to the predominant influence of some person, nation, principle, or force. Thus we speak of the "Age of Pericles," the "Roman Period," the "Age of the French Revolution," or the "Age of Electricity." Geologic history is subdivided according to great predominant physical or organic phenomena as, for example, the "Appalachian Revolution" (toward the close of the Paleozoic era), the "Rocky Mountain Revolution" (toward the close of the Mesozoic era), the "Age of Fishes" (Devonian period), the "Age of Mammals" (Cenozoic era).

Students of earth history, like students of human history, must be very careful to make a distinction between events and records of events, because by no means all historical events are recorded. Events are continuous, while their records are usually much interrupted and apparently sharply separated from each other. In both geologic and human history, times or periods of comparatively quiet and slow change have often given way to times of comparatively rapid, to even revolutionary, change.

CHAPTER VI

ORIGIN AND PRE-GEOLOGIC HISTORY OF THE EARTH

If we define geology as the study of the history of the earth and its inhabitants as revealed in the rocks, it is evident that the problems of the origin and very early development of the earth are strictly astronomic rather than geologic. It is generally agreed that geologic history did not begin till the ordinary earth processes, such as weathering and erosion, transportation and deposition of sediments, etc., began to operate. Since, however, the pre-geologic condition of the earth must have gradually given way to its geologic condition, it is a matter of interest for the geologist to consider the hypotheses regarding the very early development of the earth.

The Solar System

The sun has a diameter of about 866,000 miles, and a volume 1,300,000 times that of the earth. Around this central sun nine planets—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto—revolve in nearly circular orbits. Three of these planets—Mercury, Venus and Mars—are smaller than the earth, while the others are larger, Jupiter being 1,300 times as large. The earth is about 93,000,000 miles from the sun and requires one year for a trip in its orbit around the sun, while Neptune, a very distant planet, is about 2,800,000,000 miles from the sun and requires 164 years for a revolution about the sun. Each planet also rotates upon its axis, the earth accomplishing a rotation every twenty-four hours. Most of the planets have smaller bodies called satellites or moons revolving about them, such as Earth with its one moon, Saturn with eight moons, etc. The sun and the nine planets with their satellites, together with a group of many small independently revolving bodies called "planetoids," comprise the solar system. That this solar system constitutes only a very small part of the universe is clearly proved by the fact that the nearest fixed star is several trillions of miles from the earth.

Some of the well-known facts which any hypothesis of the origin of the solar system must explain are as follows: (1) The planet orbits are

all elliptical, but nearly circular; (2) the orbits lie in nearly the same plane; (3) all planets revolve about the sun in the same direction; (4) the sun's direction of rotation is the same as that of the planets' revolution; (5) the planes of the planets' rotation nearly coincide with the planes of their orbits (except Uranus and Neptune); (6) the direction of the planets' rotation is the same as that of their revolution; and (7) the satellites revolve in the direction of rotation of their planets (two or three exceptions).

Hypotheses of Earth Origin

Nebular or Ring Hypothesis. In 1796 Laplace published a remarkable work on astronomy, and in it, incidentally, he put forth his now well-known hypothesis regarding the origin of the solar system. He postulated a spheroidal mass of very highly heated, incandescent gas or nebula greater in diameter than the present solar system, this whole mass rotating in the direction of the revolution of the existing planets. Due to loss of heat by radiation, this mass contracted and its shrinkage necessarily made it rotate more rapidly upon its axis, at the same time causing the centrifugal force on its outside to become stronger and stronger. Finally the centrifugal force at the equator became equal to the force of gravity and the equatorial portion was left off (not thrown off) as a ring surrounding the contracting remainder. The materials of the ring condensed to form the outermost planet. By continued contraction of the rotating nebula, the other rings and planets were formed. The satellites were produced in a similar manner by rings left off by the shrinking planets.

Briefly, according to this hypothesis, the earth was originally highly heated and much larger than now. During its cooling and contraction, its original hot and dense atmosphere, which contained all the earth's water in the form of vapor, gradually became thinner due to absorption by the earth. When the conditions of pressure and temperature were favorable, water vapor condensed to form the hydrosphere. The oldest rocks must have been igneous, that is, they were portions of the original crust formed by cooling of the molten globe.

For over a hundred years the Laplacian hypothesis exerted a profound influence upon science, philosophy, and theology, and certainly many of the important phenomena of the solar system are explained by it. Some serious objections to it may, however, be briefly stated as follows: (1) Nearly all existing nebulae are spiral and not circular; (2) spectroscopic study shows that these nebulae do not consist of gas, but rather of

discrete liquid or solid particles; (3) the backward revolutions of certain satellites oppose the hypothesis; (4) rings could not have been left off, that is, there could have been no intermittent process of the sort; and (5) it is not at all clear how the matter of the rings could have condensed into planets.

Planetesimal or Spiral Hypothesis. It is a remarkable fact that, although many thousands of nebulae are known, there are very few examples of ring nebulae of the Laplacian type among them. Spiral forms are very common, especially the smaller ones. Also, as above stated, spectroscopic study of these nebulae shows them to be made up of discrete (liquid or solid) particles rather than of gas. The Planetesimal hypothesis, formulated by Chamberlin and Moulton, "postulates that the matter of which the sun and the planets are composed was, at a previous stage of its evolution, in the form of a great spiral swarm of discrete particles whose positions and motions were dependent upon their mutual gravitation and their velocities" (Moulton). A nebula of this sort comprised a luminous central mass (the future sun) from the opposite sides of which two luminous spiral arms streamed out with occasional larger masses or knots along each arm, and with dark lanes between the arms (see Fig. 16). Also some nebulous matter occupied the spaces between the arms. Such a distribution of matter in a spiral shows that the form could not have been maintained by gaseous pressure, as in the Laplacian hypothesis, but rather by the movements of the separate particles or masses. Since these particles are thought to have moved like miniature planets, they are called planetesimals. Each planetesimal is considered to have moved in its own orbit around the central mass. The planetesimals did not move along the arms of the spiral, but rather crossed them at considerable angles (Fig. 17). "When we see a spiral we do not see the paths which the separate masses have described, but the positions

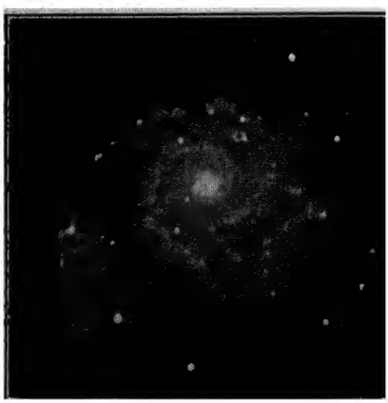


FIG. 16. A very symmetrical spiral nebula in Pisces (M. 74). Photo by Lick Observatory. (From Chamberlin and Salisbury's "Geology," permission of Henry Holt and Company.)

which they occupy at the time. In the present case (Fig. 17) if a smooth curve is drawn through the regions where the matter is densest, it will form a sort of double spiral as represented by the full lines" (Moulton). The dotted lines in the figure represent orbits of some of the particles or knots.

The planetary bodies, including the earth, began as hot gas-bolts shot out from the sun, and, in cooling, each of these gas-bolts condensed to a nuclear body or knot associated with myriads of planetesimals. Largely because of the crossing of orbits, the knots or nuclei increased in size by

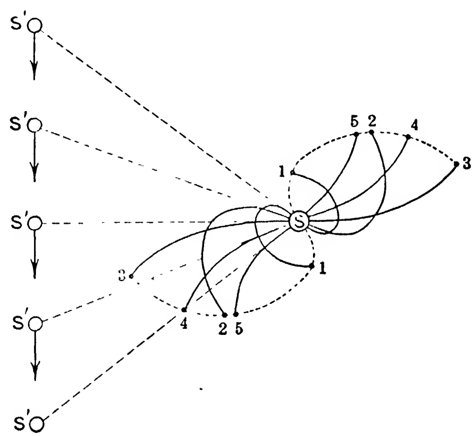


FIG. 17. Diagram to illustrate the formation of a spiral nebula. S, sun; S', passing star whose direction of passage is shown by the arrows. The curved lines show the paths followed by nuclear (planetary) masses (numbered dots) pulled out from S by S'. The straight lines are the paths which the planetary masses would have followed had S' remained stationary in each of the positions indicated. The curved dotted lines pass through zones containing planetary and other nuclear masses, thus producing the two luminous spiral arms of the nebula. (Modified after Moulton.)

a gathering in or accretion of planetesimals. Meteorites, which now strike the earth, are thought to be planetesimals still gathering in, though at a very slow rate.

The origin of the spiral is believed to have been caused partly by strong tidal disrupting effects generated in the central body (sun) by a passing star, and partly by eruptive activity of the sun itself. The separated masses at first moved straight toward the passing star, but, because of change in position of the passing body, they gradually became pulled around and their paths curved into spirals as shown by Figure 17. In accordance with the principle of the well-known tide producing force,

similar masses must also have shot out from the opposite side of the sun or central body. Finally, when the passing star had so far gone by as to have largely lost its power of very effectively attracting the sun, the spiral orbits of the planetesimals and larger planetary bodies gradually became coiled into elliptical, nearly circular orbits around the sun which then became the central attracting body.

Briefly, according to this hypothesis, the earth was never, except in its very early nuclear stage, a highly heated gas and never necessarily more highly heated than at present, hence sedimentary as well as igneous materials may well be expected among the earliest formed rocks. Instead of a much larger original earth, it increased in size by accretion of planetesimals. With increase in size came increase in force of gravity, causing compression of the earth's matter and generation of more and more interior heat (probably aided by radioactivity), thus inaugurating volcanic activity. Accompanying this increasing pressure and heat, gases (including water vapor) were driven out to form an atmosphere which gradually became larger and denser. When the water vapor had sufficiently accumulated, precipitation resulted to initiate the hydrosphere.

Modification of the Planetesimal Hypothesis. Jeans and Jeffreys have set forth what may be termed a modification of the planetesimal hypothesis, very briefly summarized as follows. The disruption of the sun by a passing star was caused by the tide producing force with little or no aid from the eruptive activity of the sun. Instead of hot gas-bolts shot out from the sun from time to time, a long streamer of very hot gas was steadily pulled out of the sun by the passing star and drawn forward by the star. This streamer, which reached to the outer boundary of the solar system, became disrupted into ten parts which formed into spheres—nine of them planets, and one of them the group of the planetoids. When the passing star moved far enough away the planetary bodies, then dominated by the attractive influence of the sun, began to revolve around the sun in orbits.

According to this hypothesis the earth was originally a highly heated, incandescent gas. Then it cooled to full-size molten condition. About the beginning of geological time a solid crust formed over the fluid interior. The earth was then surrounded by a very thick, hot, dense atmosphere which in time cooled enough so that its contained water vapor could condense in tremendous quantities and thus produce the oceans. As cooling and solidification proceeded, lighter rocks were formed in the outer shell of the earth, and heavier and heavier material downward toward the center.

Was the Earth once Molten? Certain facts about the present-day earth rather strongly indicate that it was once in a molten condition. Thus the specific gravity of the earth as a whole is much higher than that

FIG. 18. Map of North America, showing its main political and physical divisions.

of its outer shell. In a molten earth the heavier materials would naturally gravitate toward the center. Also studies of the passage of earthquake waves in the earth, particularly their velocities, strongly indicate the existence of several earth-shells—an outer shell of lighter (granitic) rocks about 37 miles thick; a deeper shell of distinctly heavier (basaltic) material about 1800 miles thick; and a central still heavier liquid or metallic core over 4000 miles in diameter. Earthquake waves of trans-

verse vibrations do not pass through the great central core. Such waves, as far as definitely known, pass through solids only, and hence the inner part of the earth is probably still molten.

Certain other facts seem opposed to a once molten globe. Thus climatic changes and conditions necessary for living things were, in earlier geological time, essentially like those of today, so how could there have been a very hot, dense, enormous atmosphere which has gradually diminished in all these respects? Also "a globe, whose mobile liquid material has been arranged in accordance with its density . . . , possesses little potential opportunity for deformation, except for shrinkage due to cooling. . . . Cooling from the earliest solidification to the present earth temperatures would not cause enough contraction to account for the wrinkling which the earth shell shows today." (R. T. Chamberlin.)

CHAPTER VII

THE ARCHEOZOIC ERA

THE OLDEST KNOWN GEOLOGICAL RECORDS

IN earth history, as in human history, the recorded events of earliest times are fewest and most obscure, and hence the least intelligible of all. In spite of a certain disadvantage in beginning with the least known part of the history of the earth, the only satisfactory method of presenting the subject is "to follow the natural order of events. This has the great advantage of bringing out the philosophy of the history—the law of evolution" (J. Le Conte). The earliest known geological history is recorded in the rocks of the Archeozoic group, often called the Archean. While it is true that the most obscure records of any rock group are here, partly because the original structures of these rocks have generally been so profoundly changed (metamorphosed) and partly because of the almost complete absence of well-defined fossil forms, nevertheless, certain very definite and important conclusions regarding the earliest known era of geologic time may be reached through a study of the Archezoic rocks which are believed to be more than one billion years old.

GENERAL NATURE AND ORIGIN OF THE ARCHEOZOIC ROCKS

"Archean Complex," "Basal Complex," "Fundamental Complex," etc., are all terms which have been applied to the rocks of the Archeozoic group which invariably occupy a basal position with reference to all other rock groups. The Archeozoic group is a crystalline complex, comprising various kinds of igneous rocks and metamorphosed strata, beneath the base of the more or less well-determined sedimentary succession.

Briefly stated, the Archeozoic group exhibits the following characteristics: (1) So far as observed, it always shows a profound unconformity or erosion surface at its summit; (2) its lower limit or base has never been determined, and is likely inaccessible; (3) its thickness is very great, at least tens of thousands of feet, and possibly many miles; (4) its rocks are always crystalline and usually highly metamorphosed and

tilted or folded; (5) it comprises a most heterogeneous group of rocks, often intimately associated, such as lavas and tuffs; schists, quartzites, and marbles, representing shales, sandstones, and limestones which have been highly metamorphosed; some beds of iron ore; and great volumes of plutonic rocks, especially granites and granitic gneisses; (6) the igneous rocks almost always greatly predominate, particularly in its lower portion; (7) it rarely, if ever, contains distinct fossils, though certain evidences of life do exist; and (8) as far as known it is universall' present at or under the earth's surface.

The Archeozoic has been more or less studied in various countries, and the above named features always appear to characterize it. Caution must be exercised, however, in assigning groups of rocks in different regions to the Archeozoic merely because they present some or many of these characteristics. Many rocks formerly classed with the Archeozoic have been proved to be of later age. If rocks with all the characteristics of Archeozoic lie below definitely determined (by fossils) Cambrian strata, and are separated from the Cambrian by a great series of sedimentary or metamorphic rocks (Proterozoic), then we may be fairly certain that the rocks belong to the Archeozoic group. If crystalline rocks of Archeozoic appearance are directly overlaid by Cambrian strata, or by Mesozoic strata, the crystalline rocks in the first instance may be either Archeozoic or Proterozoic, and in the second instance of any age preceding the Mesozoic era.

Distribution of Archeozoic Rocks

As far as known, Archeozoic rocks appear to be universally present at or below the earth's surface. If this be true, and all evidence strongly favors such a view, it is a most remarkable characteristic of the Archeozoic, because no other rock group has such a distribution. There is a widespread surface distribution of Archeozoic rocks, in large and small areas, throughout the lands of the earth.

On the accompanying map (Fig. 19) the surface distribution (areas of outcrops) of pre-Cambrian (Archeozoic and Proterozoic) rocks in North America is shown. Most of these areas contain more or less Archeozoic. The map shows the greatest area of pre-Cambrian rocks in North America to be around Hudson Bay. This vast area of fully 2,000,000 square miles contains much Archeozoic. Among the principal smaller areas containing Archeozoic rocks are those of Newfoundland, New England states, Adirondack Mountains, Piedmont Plateau, Michigan, Wisconsin, Minnesota, and numerous areas in Alaska, and in the

Rocky Mountain district and westward. In drilling deep wells in many places, particularly in the upper Mississippi Valley, rocks of the pre-Cambrian complex have been encountered, and so we may be confident of the presence of Archeozoic under cover of thousands of square miles

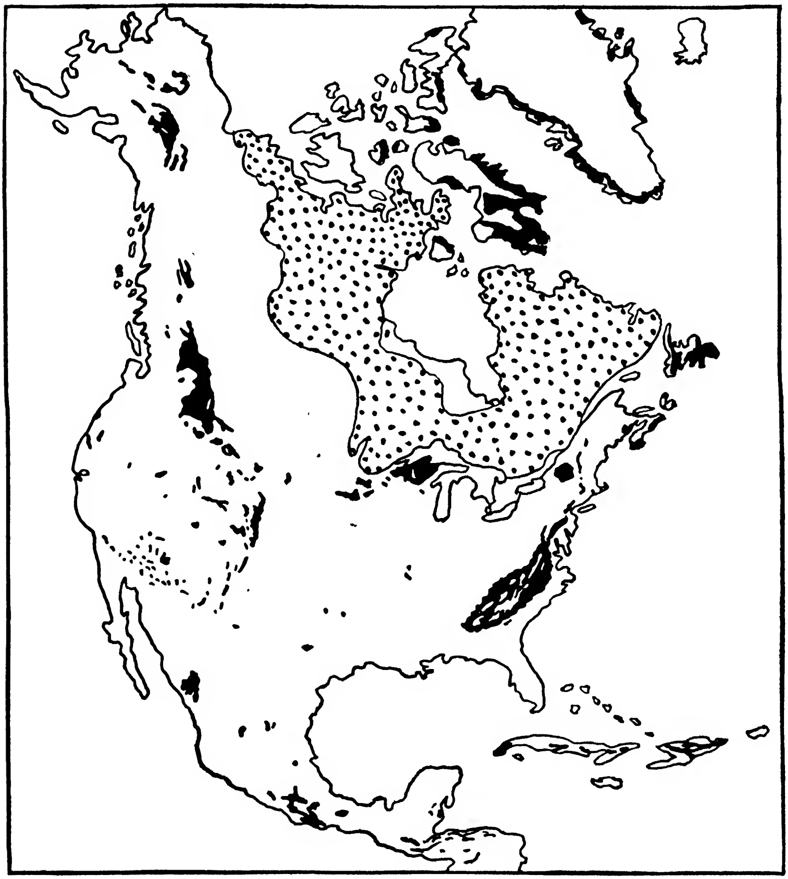


FIG. 19. Map showing the surface distribution of pre-Cambrian (Archeozoic and Proterozoic) rocks in North America. Largest area shown by dotted pattern; smaller areas by solid black. (Modified after Willis, U. S. Geological Survey.)

of later rocks. These facts of distribution, together with the fact that wherever erosion has gone deep enough the Archeozoic never fails, leave little room for doubt concerning the universal presence of these rocks in North America.

Subdivisions of the Archeozoic Group

In most regions where it has been studied, the Archeozoic group consists of two or more distinctly different classes of rocks—metamorphosed strata of various kinds, plutonic rocks of different kinds (mostly granite), and often metamorphosed volcanic rocks. In many places these rocks may be separately mapped as such, but in many others different kinds are so intimately mixed or associated as to preclude separate mapping. In every known region the very oldest are surficial rocks of either sedimentary or sedimentary and volcanic origin, and these are cut or intruded by (younger) plutonic rocks. The present state of our knowledge does not warrant the subdivision of the Archeozoic anywhere into more than two definite periods or systems. In most regions not even two such subdivisions have been determined.

The following tabular summary shows the subdivisions of the Archeozoic and their relation to the younger Proterozoic in a portion of North America where a fine display of widely exposed older pre-Cambrian rocks have been carefully studied. This may be regarded as the type Archeozoic region of the continent.

	Lake Superior-Lake Huron Region
Proterozoic	Huronian system
	(Great unconformity)
Archeozoic	Algoman granite. (Extensive batholithic intrusive bodies.) Timiskaming system, including Sudbury, Knife Lake, Seine River, Doré, and other series. (Sedimentary rocks, locally with volcanics, highly metamorphosed.) (Unconformity, small to great) Laurentian granite. Keewatin system, including the Coutchiching series. (Largely volcanic rocks, with more or less associated sedimentary material. All rocks highly metamorphosed.)

Lake Superior–Lake Huron Region

Keewatin System. The *Keewatin* system of rocks has a widespread distribution, outcropping in many large and small areas across southern Ontario in Canada, and in northern Minnesota and northern Michigan in the United States. It includes the oldest determined rocks in the region, and no rocks anywhere else are known to be older.

The Keewatin is a highly metamorphosed complex of lava-flows and tuffs with some intercalated beds of original sediments now in the form

of slates, schists, and certain iron-rich rocks. They are usually gray or dark green. Even the volcanic rocks have often been rendered schistose by metamorphism. In spite of the fact that the rocks are generally much metamorphosed, enough diagnostic features are preserved to prove their origin.

In most places the Keewatin rocks show steep dips because they have been strongly folded. They are commonly thousands of feet thick—in some places more than 20,000 feet. The full thickness is not known,

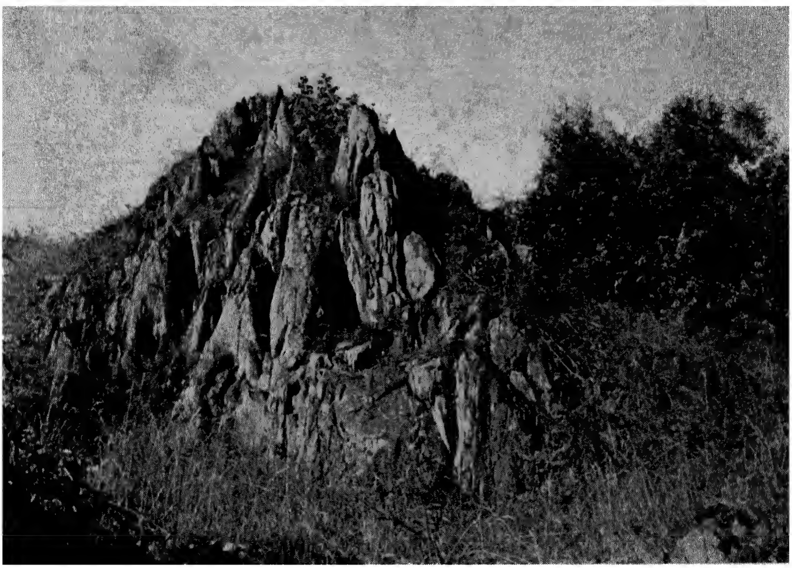


FIG. 20. A detail view of very ancient Archeozoic (Keewatin) rock. It is highly metamorphosed, schistose, volcanic rock the foliation of which shows nearly vertical dips. Ely, Minnesota.

first, because the upper part of the original pile has been profoundly affected by erosion, and, second, because the bottom of the pile has never been found. The fact that they are surficial rocks makes it certain that they must have accumulated on top of still older rocks. It would indeed be interesting to know the nature of those still more ancient rocks. Future researches may tell us, that is if such very ancient pre-Keewatin rocks still exist. If so, a still earlier chapter will be added to our knowledge of earth history.

The *Coutchiching* series comprises very ancient sedimentary rocks which have been metamorphosed mainly into slate and mica schist. In

Canada, a little west of Lake Superior, it is said to be several thousand feet thick. Its exact relation to the Keewatin is still a problem. In any case it is very closely related to, and seemingly conformable with and part of the Keewatin system. By some it is believed to overlie the Keewatin, at least in part. By others it is believed to underlie the Keewatin proper, and, if so, it is the world's oldest known rock formation.

Laurentian Revolution and Granite Intrusion. After the accumulation of the great Keewatin system of rocks, the so-called *Laurentian* granite was intruded into it in the form of batholiths throughout much of the region. The Laurentian granite is the oldest known plutonic rock. The heat and pressure of the rising magma helped to metamorphose the Keewatin rocks.

The granite intrusions accompanied a widespread though rather moderate degree of folding of the Keewatin rocks. This folding, accompanied by the intrusions and uplift, may be called the *Laurentian Revolution.* This is the earliest definitely known deformation of the earth's crust.

After (and in part during) the Laurentian Revolution, and before the next oldest (Timiskaming) rocks were formed, the whole Keewatin region was more or less deeply eroded. This we know, first, because the folds were truncated by erosion, and granite batholiths were laid bare, before the Timiskaming rocks were laid down upon them, and, second, because pebbles and boulders of both Laurentian granite and Keewatin rocks are common at the bottom of the Timiskaming system.

Timiskaming System. A great system of rocks, very largely sedimentary in origin, directly overlies the Keewatin system in many places from western Quebec westward across Ontario, and also west and south of Lake Superior. Where the rocks of this age are particularly well exposed in a large region in western Quebec and eastern Ontario, they have been named the *Timiskaming* system. Rock series such as the Sudbury, Seine River, Doré, Knife Lake, and others, which have been independently described and named in various parts of the larger region, are now rather confidently believed to represent parts or series of one great system—the Timiskaming—which is widespread throughout the Lake Superior-Lake Huron region.

The basal portion of the Timiskaming system is nearly always a great conglomerate formation. In regard to this conglomerate in the type region of the Timiskaming, H. C. Cooke says: "The thickness of the basal conglomerate varies from zero to many thousands of feet, fre-

quently within short distances along the strike, and this, together with other characteristics, such as lack of rounding of the pebbles in many places, suggests that it is of subaerial origin, probably laid down as alluvial fans or cones. The conglomerate contains pebbles of all the Keewatin rocks, both volcanic and sedimentary, and also great numbers of pebbles of various granitic rocks. It is evident, therefore, not only that the conglomerate overlies the Keewatin with unconformity, but also that the Keewatin was intruded by (Laurentian) granite bodies which were unroofed by erosion prior to or during the deposition of the Timiskaming system."

The upper portions of the Timiskaming system consist largely of quartzites, slates, schists, graywackes, and so-called iron formation, often

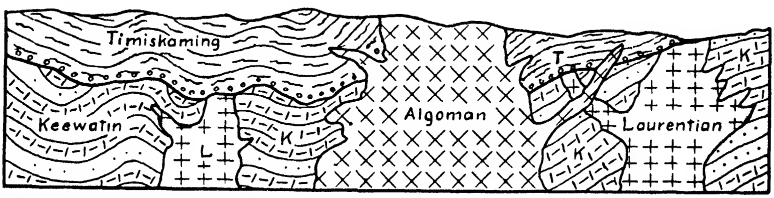


FIG. 21. A highly generalized section, about 25 miles long, showing the relations of the Archeozoic group of rocks in the Lake Superior-Lake Huron region of Canada. The Keewatin system was moderately folded and intruded by the Laurentian granite, after which there was deep erosion. Then the Timiskaming rocks were laid down, and later strongly folded and intruded by the Algoman granite, after which there was another period of profound erosion, marked by the upper surface.

with interbedded lavas and tuffs. Crystalline limestone seldom occurs. Nearly all of the now altered sediments seem to be of non-marine or continental origin. The whole system in places, such as the Lake Timiskaming and Sudbury regions of Ontario, reaches a thickness of 20,000 feet or more. Thicknesses of thousands of feet are common.

There has been some difference of opinion as to whether the Timiskaming should be regarded as Archeozoic or Proterozoic. Several careful students of the subject have pointed out that the Timiskaming and Keewatin are distinctly more closely related than the Timiskaming and the next overlying (Lower Huronian) rocks of Proterozoic age. Thus the erosional surface (unconformity) separating the Timiskaming and Keewatin, and also the structural differences and degree of metamorphism of the two systems, are much less pronounced than those between the Timiskaming and Lower Huronian. For these reasons it seems best to classify the Timiskaming with the Archeozoic.

Algoman Revolution and Granite Intrusion. After the great Timiskaming system of sediments and associated volcanics was laid down, the Lake Superior-Lake Huron region experienced a second period of strong diastrophism—this time much more intense than that of the first (Laurentian) disturbance. It has been called the *Algoman Revolution.* Accompanying the orogenic movements, great and widespread batholiths of plutonic rocks, commonly called *Algoman* granite, broke into, cut to pieces, and helped to disturb and metamorphose both the Keewatin and Timiskaming systems.

"The pre-Timiskaming (Laurentian) folding, important as it was, was only a minor movement compared with the great (Algoman) folding that succeeded the Timiskaming deposition and closed the Archean (or Archeozoic) era. So powerful was the compressive stress behind the latter movement that the Keewatin and the Timiskaming systems, with a combined thickness of many miles, were crushed into (mountain) folds with almost vertical dips on the flanks, while the less competent members (beds) were rendered schistose. This movement was closely followed (or accompanied) by the intrusion of the great batholiths of (Algoman) granite that now outcrop over immense areas. . . . Then followed an erosion interval of great length during which the mountains were entirely levelled, and the peneplain was formed on which the Huronian lies wherever found" (H. C. Cooke).

Not only in the Canadian region, but wherever the Proterozoic rocks of North America have been found resting upon the Archeozoic, the two sets of rocks are separated by a profound unconformity representing a very long interval of erosion. Evidently North America stood well above the sea for a long time, and was nearly leveled by erosion, before the oldest known Proterozoic strata were laid down.

Archeozoic of Southeastern Canada and Northern New York

Throughout southeastern Ontario, southern Quebec, and the Adirondack Mountains of northern New York, the oldest known pre-Cambrian rocks are highly metamorphosed sediments constituting the great *Grenville* system. It is many thousands of feet thick. It consists largely of schists, quartzites, and crystalline limestones representing highly metamorphosed shales, sandstones, and limestones. Some altered igneous rocks seem to be contemporaneous with the strata. The Grenville strata have been so profoundly changed from their original condition that certain of the highly sedimentary features have been completely obliter-

ated. Thus the absence of water-worn particles and fossil forms, both of which are so characteristic of ordinary strata, is due to complete crystallization (metamorphism) of the Grenville strata since their deposition. There are, however, certain proofs of the sedimentary origin of the Grenville. The fact that these rocks commonly occur in alternating layers, which stand out in sharp contrast because of marked differences in composition and color, furnishes strong evidence that this distinct banded effect is due to differences in original sedimentation (Fig. 22). A great mass of igneous rock is generally characterized by more or less homogeneity throughout; a mass of typical sediments, on the other hand, is arranged in distinct layers, such as shale, sandstone, or limestone which

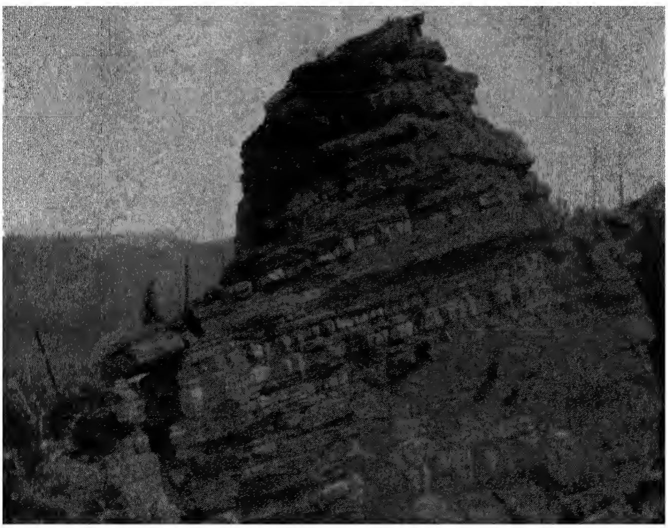


Fig. 22. Archeozoic (Grenville) metamorphosed strata in the central Adirondacks. Note the distinct stratification in these highly crystallized rocks.

show frequent differences in composition. In the Grenville there are extensive beds of crystalline limestone and quartzite, and such rocks could not have been of igneous origin. In some places the strata are so filled with graphite flakes that the mineral is mined. Carbon existing under such conditions is doubtless of organic origin and represents (in crystallized form) the final stage in the decomposition of organisms which lived in the waters while the Grenville strata were being deposited.

In the western part of southeastern Ontario the Grenville contains some altered lava-flows, and it is there overlain unconformably by the *Hastings* system of metasediments at the base of which there is a conglomerate formation.

After the deposition of the Grenville-Hastings strata, igneous activity took place on a grand scale throughout southeastern Canada and northern New York. Tremendous bodies of molten rock, varying in composition from gabbro to granite, were forced into the strata from

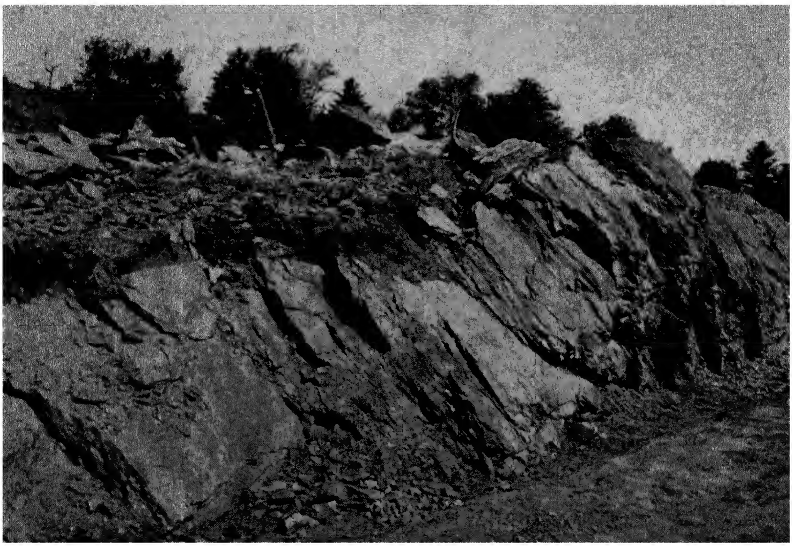


FIG. 23. An exposure of steep-dipping Timiskaming (or Sudbury) metasedimentary rocks (schists and quartzites). Near Walford, Ontario, Canada.

below. The present distribution and mode of occurrence of these igneous rocks shows that the molten masses broke into the Grenville strata in a very irregular manner. In most cases the strata were pushed aside, broken up and tilted, or domed by the rising molten floods; in many cases magmatic materials intimately penetrated the strata; often large and small masses of the country rocks were enveloped in the molten floods; in some cases portions of the strata were digested or assimilated by the magmas; while in other places parts of the Grenville were left intact and scarcely disturbed.

After the disturbance of the Grenville system, and the intrusion of the great batholiths into it, the whole area of southeastern Canada and northern New York was subjected to very profound erosion.

The Grenville has never been definitely correlated with any rock system or series farther west in Ontario. The fact that it is universally so highly metamorphosed points strongly to its great antiquity. Except for the fact that the Grenville (metasediments) and Keewatin (largely metavolcanics) are different in origin, the Grenville-Hastings-batholith succession suggests correlation with the Keewatin-Timiskaming-batholith succession farther west.

Archeozoic Rocks Elsewhere in North America

In the vast region of pre-Cambrian rocks surrounding Hudson Bay (Fig. 19), there are many occurrences of Archeozoic rocks more or less similar to those already described.

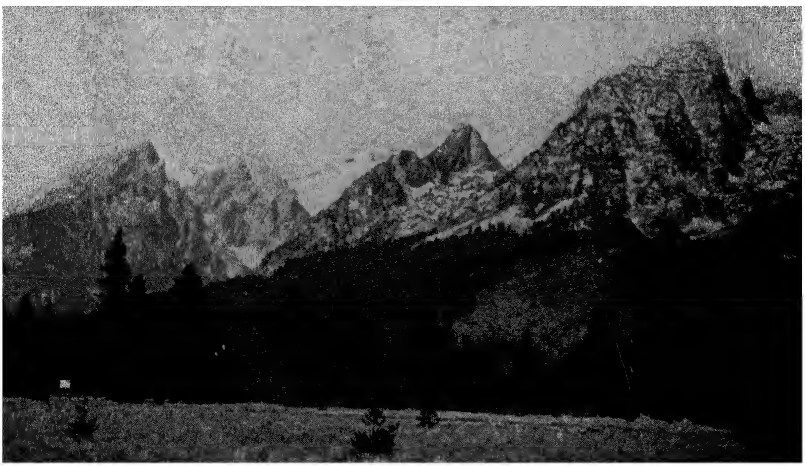


Fig. 24. Mountains of Archeozoic granite rising to heights of 13,000 feet or more above sea level. Teton Range in Grand Teton National Park, Wyoming.

Rocks quite certainly of Archeozoic age occur in various places in the Piedmont Plateau of the eastern United States. For example the *Baltimore* gneiss of Maryland is a very ancient sedimentary formation, highly metamorphosed and rather thoroughly injected with granite. The *Fordham* gneiss of New York City and vicinity is similar. Both of these gneisses lie unconformably below great series of metamorphosed strata which are regarded as of Algonkian (Proterozoic) age and which unconformably underlie early Paleozoic strata.

In the Rocky Mountains there are Archeozoic rocks, mainly granites, often intimately associated with still older schists in many places. Thus

they form the outcropping cores or axes of the Laramie, Wind River, Big Horn, Grand Teton (Fig. 24), Sangre de Cristo, and Colorado Front Ranges.

In the depths of the Grand Canyon of Arizona, Archeozoic rocks are exposed for many miles. They comprise the *Vishnu* system of predominantly highly metamorphosed strata—schists, quartzites, etc.—at least 25,000 feet thick, cut by numerous large and small granite dikes.

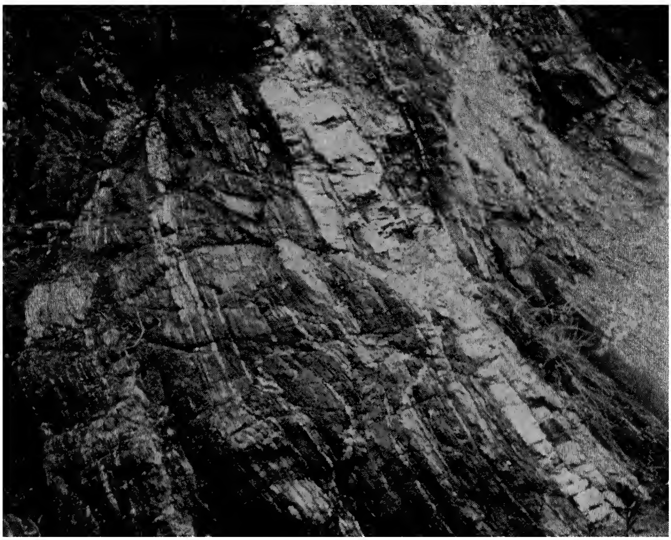


FIG. 25. A detail view of steep-dipping Archeozoic schist intimately injected, parallel to its foliation, with granite, forming a mixed gneiss. Width of outcrop about 12 feet. Western San Gabriel Mountains, California.

A very profound unconformity separates these rocks from overlying Algonkian (Proterozoic) strata.

In various parts of southern Arizona and southern California, Archeozoic metasediments, schists, gneisses, and granites and other plutonics, are well exposed (Fig. 25).

FOREIGN ARCHEOZOIC

Judging by exposures along its borders, Greenland appears to be largely occupied by Archeozoic rocks.

The Highlands of Scotland show one of the most clearly exposed areas of Archeozoic in the world, and detailed studies have shown it to be remarkably like that of the Lake Superior region.

Scandinavia exhibits the largest area of Archeozoic rocks in Europe, and considerable study has shown the rocks to be very similar to those of North America.

Archeozoic rocks are also known in Finland, France, Bavaria, Bohemia, Spain, India, Australia, China, Japan, Brazil, and other places.

Correlation of Archeozoic Rocks

Because of the complete absence of satisfactory methods of correlation, particularly the use of fossils, Archeozoic rocks in one region usually cannot certainly be regarded as equivalent to those in another region far separated from it. Thus the Grenville of eastern Canada cannot at present be certainly correlated with the older pre-Cambrian of the Lake Superior region, though considerable evidence points to such a correlation.

An old pre-Cambrian rock formation or series in one region or district may be lithologically much like one in another region, but this is in itself not a sufficient reason for correlating the two because similar rocks may be formed in very different geological ages. Because of differences in conditions for metamorphism "ancient-looking rocks in one locality may be really younger than less metamorphosed rocks elsewhere."

It must be remembered that the Archeozoic represents a vast length of time. In fact the Archeozoic era may have been longer than all subsequent time, particularly if the Planetesimal hypothesis be accepted, because, according to that view, volcanic extrusions with gradually increasing accumulation of sediments might well enough have taken place long before the earth had attained anything like its present size. Realizing the great thickness of rocks and long time which the Archeozoic presents, it scarcely seems probable that its base, or even the base of that portion which carries sediments, is anywhere exposed to view. Bearing these things in mind we also see that though in many regions rocks may be confidently referred to the Archeozoic group, nevertheless, such rocks may really represent vast age differences within that group.

Life and Climate of the Archeozoic Era

If the term "Archeozoic" is properly applied, rocks of that age should show the earliest evidences of life. Beds of graphite-rich schists; numerous scattering flakes of graphite in certain Archeozoic crystalline limestones and quartzites; extensive beds of limestone; and beds of iron

ore which were derived from carbonates, altogether quite certainly imply the existence of life in Archeozoic time. Limestone has sometimes been of chemical origin, but the presence of clearly bedded graphitic schists and crystalline limestones in a distinctly sedimentary system of rocks almost certainly shows the influence of organisms in the production of both the graphite and the limestone. "Since we know that algae alone are capable of chemically precipitating lime carbonate, the presence of enormous quantities of (Archeozoic) limestone in this region (southeastern Canada), now mainly altered to marble, strengthens the evidence in favor of life in the Archeozoic."

Fossil forms of low-order single-celled plants (algae) have been reported from Archeozoic rocks in Minnesota.

Certain hemispherical masses (called "Eozoön"), made up of indistinct, crudely concentric layers of carbonate of lime, were found many years ago in the Grenville limestone. They were probably secreted from water by primitive algae as were similar, better preserved masses occurring in Proterozoic limestones (Fig. 34).

The later Archeozoic (Seine River) crystalline limestone in the Rainy Lake region of southwestern Ontario has yielded crude, cone-shaped masses (called "Atikokania") several inches or more in diameter. They have both concentric and radial structures. Their origin is not positively known, but they probably represent single-celled plant secretions.

With the exceptions above mentioned, almost nothing like determinable fossil forms have been found in Archeozoic rocks, and even if such ever were present they must have been almost entirely obliterated by the intense metamorphism to which the rocks have been subjected. In the light of the evolution which took place during much better known geologic time, it is quite certain that the Archeozoic organisms must have been much simpler forms than those of the early Paleozoic which, in turn, were much simpler than those of the present day.

All we can say about Archeozoic climate is that, during most or all of the time, it was favorable for the existence of life and for ordinary geologic processes such as erosion and sedimentation.

Economic Products

Iron ore in workable beds occurs in the Archeozoic rocks of the Vermilion district just west of Lake Superior (Fig. 35), but most of the great iron-ore deposits of the Lake Superior district are in Proterozoic rocks.

The Grenville system contains valuable marble deposits, large quarries being operated at Gouverneur, New York.

Algoman granite and related plutonics are quarried for building stones in many places.

The plutonic rocks of the Adirondack Mountains, New York, contain large and valuable magnetic iron ore deposits.

Large quantities of graphite (so-called "black lead") have been obtained from graphitic schists in the Adirondack Mountains.

Great gold deposits are mined in southeastern Canada, especially in the Porcupine and Kirkland Lake districts of eastern Ontario. The ore occurs in veins in Archeozoic rocks. These rich metal-bearing veins were produced from gold-rich magmatic solutions which emanated from batholiths of Algoman granite when they were intruded into the Archeozoic rocks.

CHAPTER VIII

THE PROTEROZOIC ERA

THE Proterozoic era, represented by the Proterozoic group of rocks, includes the time between the Archeozoic era and the earliest Paleozoic (Cambrian) period, the Cambrian comprising the oldest known rock system with abundant fossils. The term "Algonkian" was at first, and still often is, applied to the group of rocks now more generally and satisfactorily called Proterozoic.

GREAT UNCONFORMITY BETWEEN THE ARCHEOZOIC AND PROTEROZOIC GROUPS

As already stated, whenever observations have been made under favorable conditions, the summit of the Archean complex appears to be marked by a profound unconformity. Such an unconformity, however, cannot be universal because the very fact of extensive erosion of certain areas implies the deposition of the eroded sediments in other areas. Such sediments, if found, would contain the records of the time interval indicated by the great unconformity. So far at least, this sedimentary record has not been brought to light, probably either because (1) these sediments were deposited in ocean basins not since exposed as dry land; or (2) these sediments are not at present exposed to view because concealed under later formations; or (3) these sediments have not been recognized as such. Also it is not at all unlikely that some or even many of these sedimentary areas may subsequently have become land areas so that, as a result of erosion, more or less of the sediments were there removed again to be deposited as Proterozoic or later sediments. Future researches may bring to light some of the now "lost records" which represent the great unconformity or time gap between the Archeozoic and Proterozoic.

GENERAL NATURE AND ORIGIN OF THE PROTEROZOIC ROCKS

The Proterozoic group includes all the stratified rocks and their metamorphosed equivalents, together with associated igneous rocks,

which occupy a stratigraphic position between the earliest Paleozoic (Cambrian) and the Archeozoic. Stratified rocks greatly predominate over igneous rocks, and some fossil remains of both plants and animals occur in them.

An important feature, especially of the later Proterozoic rocks, is the frequent presence of great series of non-metamorphosed strata which are therefore the oldest known unaltered strata of the geologic column. Such strata include all common types of sedimentary rocks as conglomerates, sandstones, shales, and limestones. Basal conglomerates, which were derived from the lands over which the Proterozoic seas at various times spread or transgressed, are frequently found at the bottoms of the great sedimentary series. Other great series of Proterozoic rocks of undoubted sedimentary origin are more or less metamorphosed to schists, quartzites, and crystalline limestones. The earliest Proterozoic sediments were derived from exposed portions of the Archeozoic, while later Proterozoic sediments may have been derived either from exposed Archeozoic or older Proterozoic. That the processes of sedimentation during the Proterozoic era were essentially the same as those of today is clearly proved by the very character of the sediments, the typical stratification to even lamination, shallow-water marks, etc.

Associated with the great sedimentary deposits, more or less igneous rock occurs locally both as intrusions into the strata and as extrusions or lava-flows. Granite batholiths intruded the Proterozoic rocks at or near the close of the era.

In addition to the frequent metamorphism, the Proterozoic rocks have often been subjected to great deformative movements in the earth's crust so that the rocks have either been tilted or highly folded. Sometimes they have been infolded among the Archeozoic rocks.

Distribution of the Proterozoic Rocks

Perhaps the largest Proterozoic area in North America is that in the Rocky Mountains of the northern United States and southern British Columbia. The well-known Lake Superior-Lake Huron district of Proterozoic is also of large extent. There are considerable areas in eastern Canada west of Hudson Bay, and smaller areas in Newfoundland, Nova Scotia, the Piedmont Plateau, at several places in the Mississippi Basin, Texas, Arizona (especially in the Grand Canyon), Nevada, eastern California, and at various places in the Rocky Mountain system of the United States and Canada.

Nearly all of the known outcrops of Proterozoic rocks occur within the areas of pre-Cambrian rocks shown in Figure 19.

Subdivisions of the Proterozoic Group

In many regions where detailed studies have been made, the Proterozoic group may be subdivided into from two to four systems or series separated by distinct unconformities. In some places only one division has been recognized. At present no such subdivision into series or systems has a world-wide or even continent-wide application. Generally each of these divisions shows a thickness of at least a few thousand feet, while the whole Proterozoic group has a maximum thickness of many thousands of feet, or, according to some estimates, at least ten miles as in the Lake Superior district. These subdivisions or series of Proterozoic rocks will perhaps be best understood by briefly describing a few of the better known regions.

Lake Superior-Lake Huron Region

One of the best and most carefully studied Proterozoic districts in the world is the Lake Superior-Lake Huron region. Proterozoic surficial rocks are there arranged in four distinct, lagely sedimentary divisions separated from each other by unconformities, and named Lower Huronian, Middle Huronian, Upper Huronian (Animikian), and Keweenawan. At some localities not all of these divisions are represented. The relations of the divisions to each other and to the Archeozoic below and Paleozoic above are brought out in the accompanying tabular arrangement. As indicated by the unconformities, the deposition of each division was succeeded by emergence of the region accompanied by erosion, and this in turn followed by submergence accompanied by deposition of the next division. Such repeated changes of relative level between land and sea, as here recorded for Proterozoic time are among the most common and important phenomena of geologic history.

The *Huronian* rocks are principally gray and green quartzites, schists, slates, crystalline limestones, conglomerates, and beds of iron ore, all of which are more or less metamorphosed sediments. The original strata were largely laid down under water, probably sea water, but continental deposits are often prominent. Some igneous rocks, both intrusive and extrusive, are included in the Huronian system. The Lower and Middle Huronian are usually much more metamorphosed and folded than the Upper, the latter being at times scarcely at all

deformed or metamorphosed. Estimates show the aggregate (maximum) thickness of the Huronian rocks to be no less than two or three miles.

In the type region, on the north side of Lake Huron, the *Huronian* system, 12,000 to 30,000 feet thick, is separated by unconformities into a Lower (*Bruce*) series, a Middle (*Cobalt*) series, and an Upper

		Lake Superior–Lake Huron Region
Paleozoic		Cambrian or Ordovician strata
		(Great unconformity)
Proterozoic		Killarney granite. (Batholithic bodies)
		Keweenawan system. (Volcanic and sedimentary rocks, with little or no metamorphism)
		(Unconformity)
	Huronian system	Upper (Animikian and Whitewater) series. (Mainly sedimentary moderately metamorphosed)
		(Unconformity)
		Middle (Cobalt) series. (Mainly sedimentary, moderately metamorphosed)
		(Unconformity)
		Lower (Bruce) series. (Mainly sedimentary, much metamorphosed)
		(Great unconformity)
Archeozoic		Algoman granite

(*Whitewater*) series. They are all more or less metamorphosed strata consisting largely of quartzites, conglomerates, slates, and crystalline limestones. The Huronian system there rests upon profoundly eroded Archeozoic rocks.

A formation of unusual significance is a conglomerate or boulder clay, representing a thoroughly solidified glacial deposit, at the base of the Middle Huronian series. This deposit has been observed at many places within an area of thousands of square miles north of Lake Huron. It contains "angular and subangular boulders of all sizes up to cubic yards, enclosed in an unstratified matrix. These boulders are often miles from any possible source. Striated stones have been broken out of their matrix . . . , giving still stronger proofs that the formation is ancient boulder clay" (A. P. Coleman). At some places the glaciated rock floor upon which the glacial deposit rests has been observed. There are also associated water-laid sediments. The significance of this remarkably old glacial deposit is discussed beyond.

The *Keweenawan*, or latest Proterozoic system, is characterized by a great preponderance of lava beds which constitute the lower portion of the pile; are prominent in its middle portion; and are practically absent

FIG. 26. Steep-dipping metamorphosed Huronian limestone (or marble). North Shore of Lake Huron. (Photo by T. T. Quirke for Geological Survey of Canada.)

FIG. 27. Proterozoic (Middle Huronian) glacial till resting upon Archeozoic (Keewatin) metamorphosed igneous rock, near Cobalt, Ontario. (Photo by A. P. Coleman.)

from the upper portion. Some idea of the stupendous and continuous volcanic activity of Keweenawan time may be gained from the fact that lava sheets, mostly not over a hundred feet thick each, accumulated to a depth of at least three or four miles. Between some of the later lava sheets, thin beds of sediment were deposited, while the upper part of the Keweenawan consists altogether of sediments, chiefly conglomerates and sandstones. These sediments "have characteristic reddish, yellowish, and purplish colors, and exhibit various evidences that they are essentially continental deposits formed under semi-arid conditions" (U. S. G. S.). The thickness of these sediments is about three miles, and so the whole Keweenawan system must be at least six or seven miles thick.

Toward the end of Proterozoic time, all Huronian rocks of the Lake Superior-Lake Huron region were more or less folded, and then in-

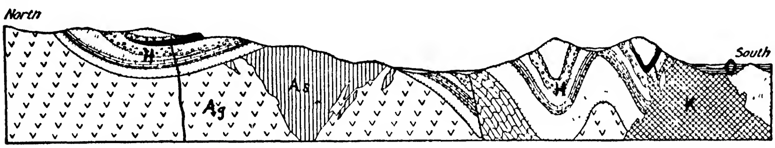


FIG. 28. North-south structure section 45 miles long on the north side of Lake Huron. Vertical scale greatly exaggerated. *As* = Archeozoic schist; *Ag* = Archeozoic granite; *H* = Huronian strata (Bruce and Cobalt series, separated by unconformity) resting by unconformity upon Archeozoic rocks; black bands = Keweenawan basic intrusive igneous rocks; *K* = late Proterozoic (Killarney) granite; and *O* = Ordovician marine strata.

The principal events recorded in this section are as follows: Archeozoic schist intruded by much Archeozoic (Algoman) granite; profound interval of erosion; deposition of Bruce strata, erosional interval, and deposition of Cobalt series; intrusion of basic igneous rocks into the Cobalt strata; intense folding in late Proterozoic time; still later intrusion of the Killarney granite; long interval of erosion; and deposition of Ordovician strata in the sea. (Section modified after W. H. Collins, Geological Survey of Canada.)

truded by batholiths of the so-called *Killarney* granite. Accompanying Figure 28 gives a good idea of the general relations of the Huronian rocks and their structures to the Archeozoic in the Huronian type region.

PIEDMONT PLATEAU REGION

Rocks generally classified as of Algonkian (Proterozoic) age occur throughout the Piedmont Plateau of the eastern seaboard of the United States. They are particularly well exposed and best known from Maryland north to the vicinity of New York City, where they comprise several metasedimentary series, thousands of feet thick, intruded by plutonic

rocks varying from granite to gabbro. In ascending order the principal metasedimentary formations or series are quartzite, crystalline limestone (marble), and schist, with some intercalated beds of metamorphosed volcanics, all in conformable arrangement. They rest by unconformity upon Archeozoic rocks. An unconformity also separates them from overlying early Paleozoic (Cambrian) strata. The accompanying table gives a good idea of the general relationships. The Proterozoic rocks of the Piedmont Plateau have been highly folded and often much faulted.

	Maryland	*New York City Region*
Paleozoic................	Cambrian strata	Cambrian strata
	(Unconformity)	(Unconformity)
	Intrusive rocks	Intrusive rocks
	Glenarm system: Peters Creek schist	
Proterozoic (Algonkian)...	Glenarm system: Wissahickon schist	Manhattan schist
	Glenarm system: Cockeysville marble	Inwood limestone
	Glenarm system: Setters quartzite	Lowerre quartzite
	(Unconformity)	(Unconformity)
Archeozoic	Baltimore gneiss	Fordham gneiss, etc.

FIG. 29. An outcrop of steep-dipping well-bedded Proterozoic (Cockeysville) marble. Near Butler, Maryland.

Proterozoic metamorphosed strata more or less similar to those of the Piedmont Plateau occur in western New England, but their classification and real extent have not yet been very definitely settled.

Rocky Mountain Region

Perhaps the largest known single area of Proterozoic rocks in North America is that in the Rocky Mountains of the northern United States

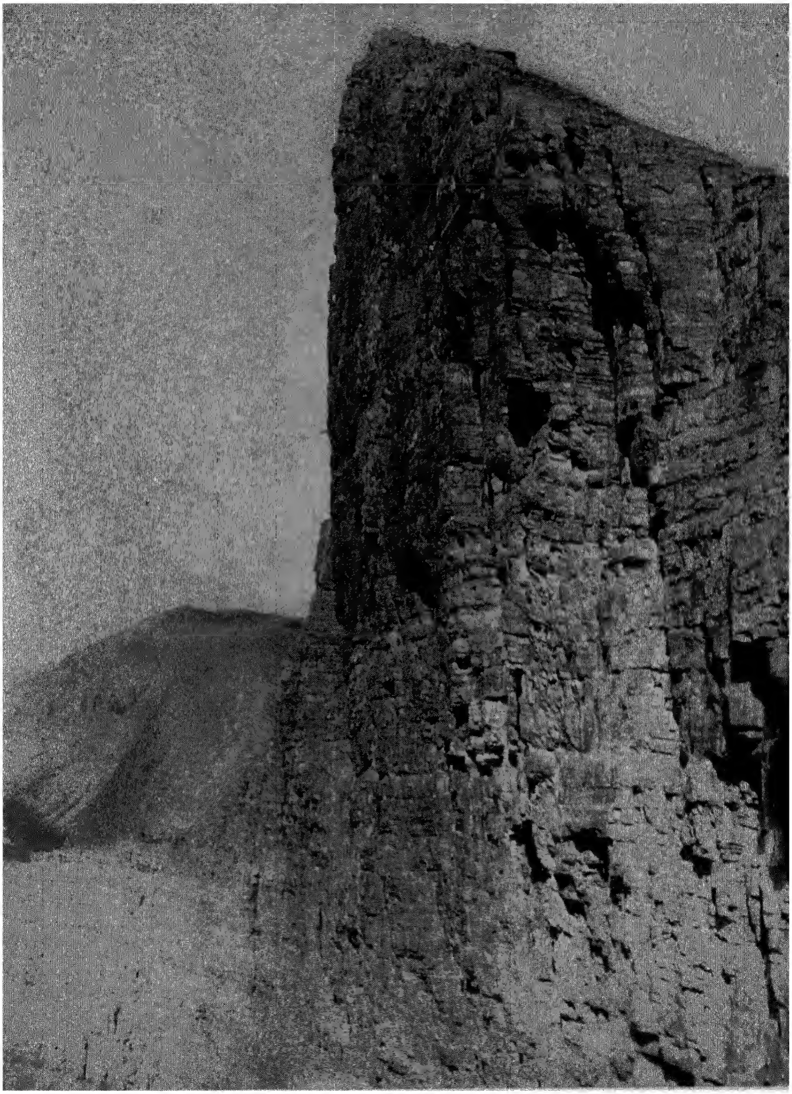


Fig. 30. Proterozoic limestone in Goathaunt Mountain, Glacier National Park. The cliff is 1200 feet high. (After B. Willis, U. S. Geological Survey.)

and southern British Columbia. These rocks generally rest upon eroded Archeozoic, and they are overlain unconformably by Cambrian or still younger strata. This unconformity may more precisely be called a dis-

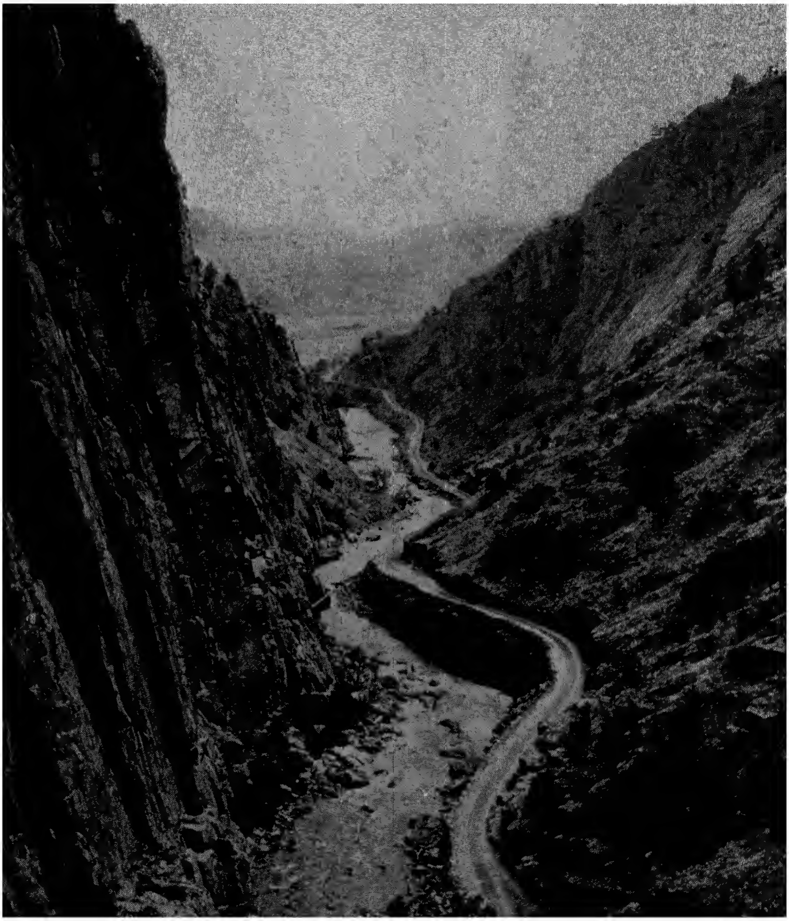


FIG. 31. Nearly vertical beds of Proterozoic quartzite on the east side of the Colorado Front Range. Thompson Canyon, Colorado. (Photo by W. T. Lee, U. S. Geological Survey.)

conformity because the Cambrian and underlying eroded Proterozoic strata usually have parallel or nearly parallel stratification surfaces. The rocks consist mostly of quartzites, sandstones, shales, and limestones, associated with remarkably little igneous rock. Their thickness is

usually two to five miles. Some of the strata (in Montana) contain fossils. Thus far no satisfactory widespread subdivision of these rocks has been determined.

In Glacier National Park, Montana, a system of practically unaltered later Proterozoic strata, fully two miles thick, forms a vast block which has been thrust faulted over late Mesozoic strata (Fig. 176). The system comprises four formations—two of limestone and two of shale, and one intrusive sheet or sill of diorite. Within the park the system of rocks shows a broad, gentle synclinal structure.

In the Rocky Mountains, 100 miles south of Glacier Park, Proterozoic strata, practically non-metamorphosed and little disturbed by folding, show great thicknesses, commonly ranging from 25,000 to 50,000 feet.

In the Belt Mountains of central-western Montana, a number of Proterozoic sedimentary formations, together called the *Belt* system, reach a total thickness of over 20,000 feet. The lower portion of this system has been metamorphosed into schist and quartzite, while the upper portion is mainly little altered shale, limestone, and sandstone. These rocks were notably folded, in part metamorphosed, and somewhat eroded before Cambrian strata were laid down upon them.

Farther south in the Rocky Mountains, metamorphosed Proterozoic strata often flank large bodies of Archeozoic rocks as in the Wind River, Big Horn, and Colorado Front Ranges. These strata usually show steep dips (Fig. 31). Similar strata are also well represented in the Uinta and Wasatch Mountains.

Grand Canyon of Arizona

Far down in the Grand Canyon of the Colorado River, there are excellent exposures of Proterozoic rocks (the *Grand Canyon* system) with their relations to the Archeozoic and the Paleozoic well exhibited. The Archeozoic rocks, comprising granites, schists, and gneisses, were profoundly eroded before the immediately overlying Proterozoic rocks were deposited. The Grand Canyon system consists of two important series. The lower one (*Unkar*), nearly 7,000 feet thick, is mostly sandstone and shale with some sills and lava-flows. The upper series (*Chuar*), separated from the lower by a slight unconformity, is over 5,000 feet thick, and it is made up of shales, sandstones, and limestones. Both series are tilted and faulted, and they are separated from immediately overlying marine Cambrian strata by a profound unconformity.

The Grand Canyon system must have been uplifted, tilted, and faulted, with production of block mountains, and then eroded to a condition of low relief, before submergence under the Cambrian sea. These historical facts are plainly indicated in Figures 32 and 33.

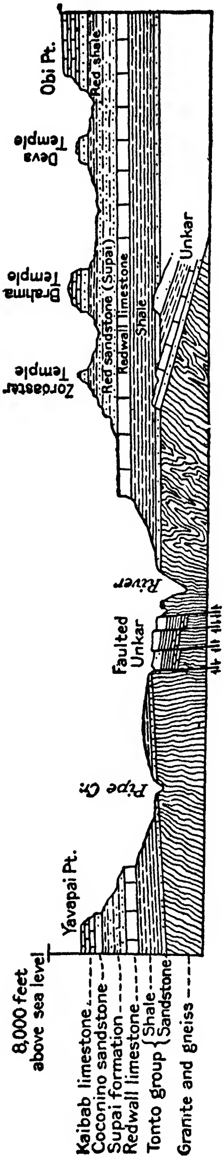


FIG. 32. Structure section across the Grand Canyon of Arizona. Granite and gneiss (or schist) are Archeozoic. Unkar is Proterozoic and Tonto to Kaibab are Paleozoic. (After N. H. Darton, U. S. Geological Survey.)

California

In the White Mountains of middle-eastern California, there is a series of several stratified, somewhat metamorphosed formations consisting of dolomitic limestone, quartzite, sandstone, and slate, several thousand feet thick. These formations are considerably folded, and they lie unconformably below Lower Cambrian strata.

Correlation of Proterozoic Rocks

The statements made regarding the difficulties of correlating the Archean rocks apply almost equally well here. Because Proterozoic rocks are more largely and distinctly sedimentary, and usually not so severely metamorphosed; usually separated into series by well-defined unconformities; and have fossils gradually coming to light in certain of the uppermost series, they afford a little more satisfactory basis for applying ordinary stratigraphic methods of correlation than do the Archeozoic rocks. Certain similarities, such as exist between the Lake Superior and Grand Canyon Proterozoic series, are highly suggestive of correlation, though far from actually demonstrable at present. Lithologic and structural similarities alone are not safe methods of correlation. Future studies, however, are quite likely to yield satisfactory results in some cases at least.

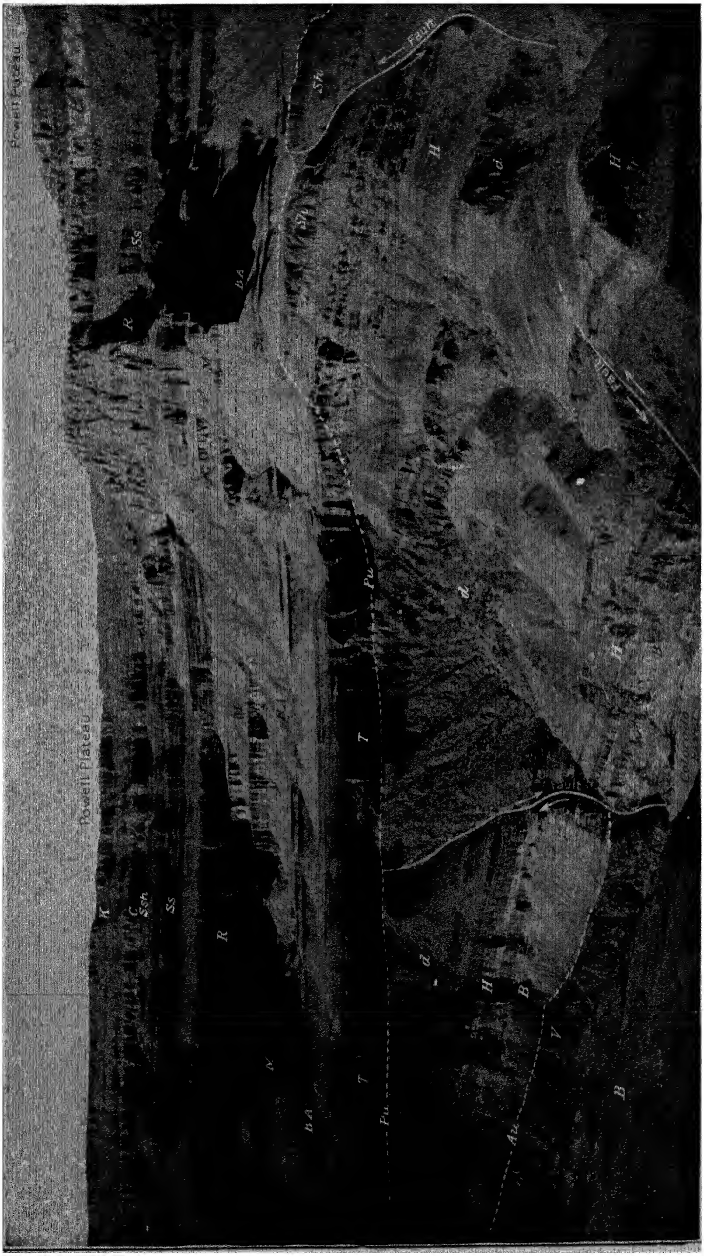


FIG. 33. A view in the Grand Canyon of Arizona (Shinumo quadrangle) exhibiting the relations of Archeozoic, Proterozoic and Paleozoic rocks to each other. *V*, Archeozoic metamorphics; *B*, *H*, *d* and *Sh*, Proterozoic partly metamorphosed strata with associated lava, *d*; *T*, *BA* and *M*, Cambrian strata; *R*, Mississippian; and *Ss*, *Ssh*, *C* and *K*, later Paleozoic. *Au*, Unconformity between Archeozoic and Proterozoic; *Pu*, unconformity between Proterozoic and Paleozoic. A vertical mile of strata is in view. Photo by Carkhuff. (After Noble, *U. S. Geological Survey Bulletin 549*.)

Not only the general lack of fossils, but also the vast length of time of the Proterozoic era, are great difficulties in the way of correlation. Considering the time necessary for the deposition of the tremendous thickness of Proterozoic rocks, and the several long unrecorded time intervals, it seems reasonable to believe that the Proterozoic era was longer even than the Paleozoic. Hence two similar series of Proterozoic rocks resting directly upon the eroded surface of the Archeozoic in widely separated regions may in reality be far different in age because the Archeozoic in one region may have remained unsubmerged very much longer than in the other. Or again, a Proterozoic series of one district may actually have been deposited during a time represented by an unconformity in another district.

Close of the Proterozoic (Killarney Revolution)

The Proterozoic era seems to have closed with North America all land, wider than at the present time, but not nearly as high on the average.

Canadian geologists have recently presented evidence to show that a mountain range at least 700 miles long, with a nearly east-west trend, was formed across middle Minnesota, northern Wisconsin, northern Michigan, and into southwestern Quebec. Late Proterozoic and older rocks were there folded, uplifted, and intruded by the Killarney granite before Cambrian strata were laid down upon the eroded edges of the Proterozoic. This range, called the Killarney Mountains, is probably the oldest known definitely located mountain range on the continent. Only the roots of it now remain.

It is quite certain that there were late Proterozoic orogenies and uplifts of strata elsewhere, as in the Grand Canyon region of Arizona; in the eastern part of the Hudson Bay region; and in Labrador. Granite intrusions accompanied the two last named orogenies.

Foreign Proterozoic

Proterozoic rocks are thought to exist in all continents. In the Highlands of Scotland, the Torridon sandstones and shales, about 10,000 feet thick, are quite certainly of Proterozoic age, since they lie unconformably between the Archeozoic complex below and well-defined Cambrian above.

The large pre-Cambrian rock area in Scandinavia, which in many respects is similar to that of Scotland, also contains considerable bodies

of sediments (at least 10,000 feet thick) of Proterozoic age. As in the Lake Superior region, iron ore occurs in some of the Swedish Proterozoic.

In Finland, France, Germany, Spain, and probably in India and Brazil, Proterozoic rocks are known.

It should be noted that in several of the foreign countries there appears to be a division of the Proterozoic group into at least two systems or series separated by unconformities.

Proterozoic Life

Some more or less determinable fossils have been found in Proterozoic strata, particularly in Montana and in the Grand Canyon of Arizona. They include algae, bacteria, worm tracks, sponge spicules, and doubtful fragments of primitive arthropods. Protozoan shells have been reported from the Proterozoic rocks of France. "The traces of pre-Cambrian (animal) life, though very meager, are sufficient to indicate that the development of life was well advanced long before Cambrian time began. . . . Stratigraphically, this fragment of what must have been a large fauna occurs over 9,000 feet beneath an unconformity at the base of the upper portion of the Lower Cambrian in northern Montana" (C. D. Walcott). In 1935 an imprint of what was probably a jellyfish was found in the Grand Canyon system. Most animals of the time were probably without shells or other hard parts, and hence were not so favorable for fossilization.

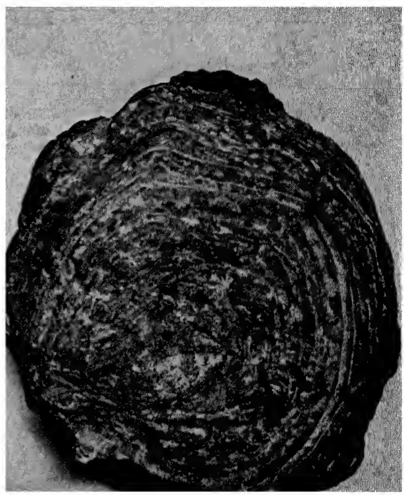


FIG. 34. A Proterozoic algal fossil from Glacier National Park, Montana. Diameter, 4 inches.

Walcott has described a number of species of limy algae from the Belt system of Montana. These algae were very simple, single-celled plants (thallophytes) which lived in water. They were hemispherical or cylindrical bodies which secreted crudely concentric layers of car-

bonate of lime from one to fifteen inches in diameter. They occur in distinct beds through hundreds or even thousands of feet of Proterozoic limestones. Well-preserved algal remains occur in the upper limestone formation in Glacier National Park (Fig. 34). Similar fossils have also been found in the Grand Canyon system in Arizona.

Walcott has described what seem to be fossil bacteria (single-celled, tiny plants) from late Proterozoic rocks. Carbonaceous material, including graphite, so often disseminated through Proterozoic shales and schists almost certainly indicate the presence of life. Likewise beds of limestone and bedded iron ores, so abundant in parts of the Proterozoic, are rarely ever known to have formed except through the agency of organisms.

Proterozoic Climate

Since the great masses of Proterozoic sediments are of quite the usual sort like those formed in later eras, and since life surely existed, we can be certain that the climate of the time was favorable for the operations of ordinary geologic processes and hence not fundamentally different from that of comparatively recent geologic time.

The widespread occurrence of a glacial deposit at the base of the Middle Huronian series in Ontario has been described. This deposit quite certainly shows that an ice sheet covered many thousands of square miles of the area between Lake Huron and Hudson Bay. It is the earliest known record of glaciation. This proof of a climatic condition favorable for glaciation so early in the earth's history is indeed significant. It shows that the temperature and atmospheric conditions of the earth nearly a billion years ago was not fundamentally different from that of the present period of geological time.

What is believed to be glacial till of Proterozoic age has also been described from South Africa.

Very distinct evidences of glaciation in late Proterozoic time are known from various parts of the world, particularly in China, India, Norway, Greenland, Australia, and western North America. A few occurrences will be described briefly.

At the bottom of the thick section of Cambrian strata in China "on the Yangtse River, 31° Lat., i.e. as far south as New Orleans, not high above sea level, a large body of glacial material (170 feet thick) was discovered. . . . It demonstrates the existence of glacial conditions in a very low latitude in the early Paleozoic" (B. Willis).

At Lat. 70° N. in Norway, glacial deposits containing clearly stri-

ated pebbles have been found resting upon a distinctly smoothed and striated surface of hard rock.

In southern Australia glacial beds of similar age and considerable thickness are distinctly folded along with the enclosing strata.

Blackwelder has recently described a glacial deposit older than Middle Cambrian, and probably of late Proterozoic age, in the Wasatch Mountains of Utah.

It seems reasonable to associate the glacial conditions with the extensive uplifts and mountain-making in so many parts of the world when the higher general altitudes of the lands caused temperatures lower than normal in the various regions.

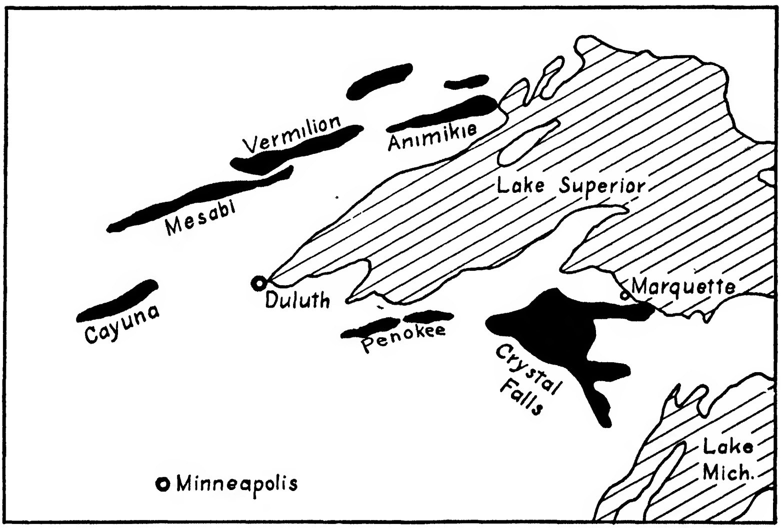


FIG. 35. Map showing locations of the great iron-ore districts of the Lake Superior region. All are Proterozoic excepting the Vermilion which is Archeozoic.

ECONOMIC PRODUCTS

The greatest iron mining region in the world is the Lake Superior district in Minnesota, Michigan, and Wisconsin. Some of these iron ores are in the Archeozoic, and some in the older Huronian rocks, but the principal deposits are in the Middle and Upper Huronian. These iron ores occur as thick beds in the sedimentary series. Often the iron ore deposits have been enriched by the work of underground waters. The Lake Superior district produces many millions of tons of iron ore yearly, or far more than the production of any foreign country.

The greatest deposits of native copper in the world are in the Keweenawan system on Keweenaw Point, Michigan. Copper has been found in small quantities in the lava beds, and underground waters have dissolved out this copper and deposited it in more concentrated form in fissures and openings of the rock, and also in porous conglomerates. Immense quantities of native copper have been mined here during the past sixty years.

The world's greatest nickel deposits occur in the Sudbury, Ontario, district where the ore is directly associated with an intrusive body of late Proterozoic gabbro.

Silver is known from various parts of southeastern Canada, the Cobalt, Ontario, district being of particular importance. The silver ores are associated with, and probably derived from, late Proterozoic gabbro intrusives.

Marble of Proterozoic age, as for example the Cockeysville marble north of Baltimore, is rather extensively quarried in the Piedmont Plateau region.

The black slate of the Peach Bottom district, Pennsylvania, is probably of late Proterozoic age.

EARLIER PALEOZOIC TIME

CHAPTER IX

ROCKS AND PHYSICAL HISTORY OF THE CAMBRIAN

The Cambrian represents the earliest period of the great Paleozoic era, and the rocks which make up the Cambrian system include the oldest known of the normal fossiliferous strata. Since these strata are the oldest which carry abundant organic remains, it follows that they are the earliest formed rocks to which the ordinary methods of subdividing and correlating rock masses can be applied. From the Cambrian on, the legible records of events of earth history are far more abundant and less defaced than those of pre-Cambrian time. From now on we shall be able to trace the changing outlines of the relief features of the continent and the evolution of organisms with some degree of definiteness and satisfaction, though a vast amount of work yet remains to be done both as regards discovery of new records and the interpretation of records old and new.

Origin of Name and Subdivisions

The oldest Paleozoic rocks were first carefully studied independently in the British Isles by the two able geologists, Sedgwick and Murchison, before the middle of the nineteenth century. Murchison applied the name "Silurian" to the great series of oldest fossiliferous strata and divided them into Lower and Upper Silurian. Sedgwick, however, considered that the very oldest fossil-bearing rocks should be separately designated, hence his application of the term "Cambrian," from Cambria, an old Latin name for a part of Wales. The Cambrian is now recognized the world over as the oldest Paleozoic system.

In North America a threefold division of the Cambrian system, with formation subdivisions in two well-known regions, is recognized as follows:

	General	*New York*	*Canadian Rockies*
UPPER CAMBRIAN	Ozarkian (Saratogan) Croixian	Little Falls dolomite Hoyt limestone Theresa formation Potsdam sandstone	Mons Sabine Sherbrooke Paget Bosworth
MIDDLE CAMBRIAN	Acadian	Stissing limestone	Eldon Stephen Cathedral Ptarmigan
LOWER CAMBRIAN	Taconian (Georgian)	Georgia formation Poughquag quartzite	Mt. Whyte St. Piran Lake Louise Fort Mountain

In the typical regions the formations usually lie one above the other in regular order without non-conformity, but careful study has shown that, passing upward in the system of strata, there is a gradual change in the character of the fossils, particularly the trilobites which are so common and widespread in the rocks. Thus the Lower Cambrian strata are generally characterized by the trilobite genus Olenellus, with its various species, and this characteristic assemblage of trilobites is called the Olenellus fauna. This does not mean that Olenellus invariably occurs in Lower Cambrian strata, or that other genera of trilobites and other fossils may not be present. In a similar way the Paradoxides and the Dikellocephalus faunas are the chief characteristics of the Middle and Upper Cambrian respectively. Such stages or life zones in the geologic column are commonly referred to as *horizons*. It should be made clear that the genus Olenellus became extinct before the Middle Cambrian strata was deposited; the Paradoxides disappeared before the Upper Cambrian was deposited; and the Dikellocephalus before the deposition of the succeeding Ordovician strata, though it is not meant that sharp lines separate these faunas. Thus each of the faunas becomes an important geologic time or horizon marker. A representative of each of these genera of trilobites is shown in Fig. 76.

These principles, here laid down as a basis for the subdivision of the Cambrian system, apply equally well to the succeeding rock systems, though many organisms other than trilobites are used for the purpose.

Distribution and Description of the Rocks

General Distribution. On the accompanying map (Fig. 36) the surface distribution of Cambrian, Ordovician, and Silurian strata is shown, that is, the locations of the areas in which such strata are known to outcrop. The principal areas of Cambrian are in New England,

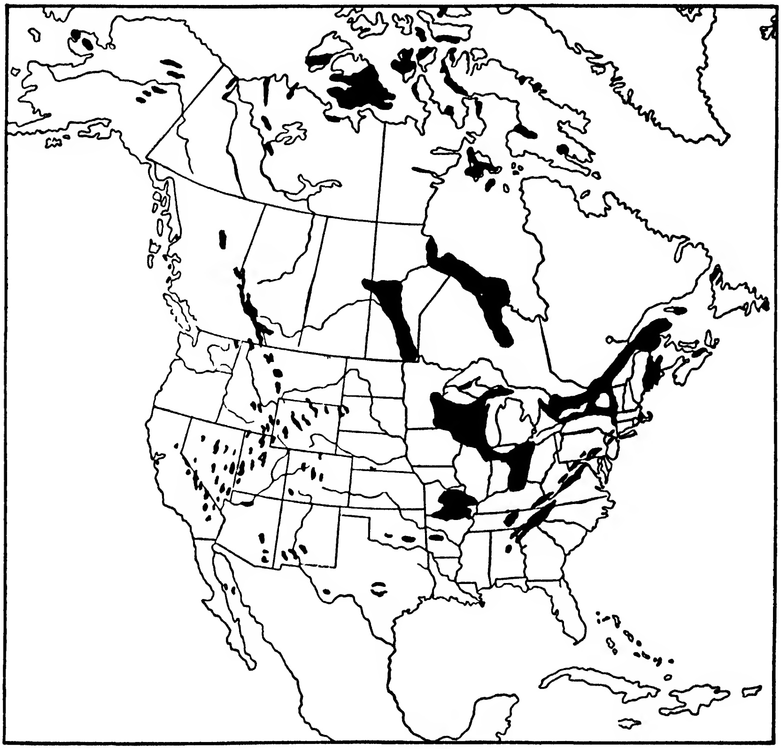


Fig. 36. Map showing known areas of outcrops (surface distribution) of Cambrian, Ordovician, and Silurian strata in North America.

southeastern Canada, New York, the Appalachian Mountains, south of Lake Superior, southeastern Missouri, Oklahoma, central Texas, Nevada, eastern California, and at various places in the Rocky Mountain region.[1] Because Cambrian rocks have so often been removed by ero-

[1] Readers who are not very familiar with the geography and physiography of the United States should, whenever necessary, refer to the map near the end of Chapter VI. Good atlas maps of North America and of the United States should also be at hand.

sion, or have been so largely covered by later sediments, or highly folded so that outcropping edges only are now exposed, the surface distribution as indicated on a map fails to give any adequate idea of the former or even present real extent of strata of this age. Thus Cambrian strata are definitely known to have been almost completely removed from several thousand square miles of the northern New York region, and Cambrian rocks have certainly been similarly removed from any other regions. Again, the distribution of the outcrops, together with many deep well sections (Fig. 6), make it certain that Cambrian strata concealed under nearly horizontal later strata spread across much, if not all, of the Mississippi Basin from the Rockies to the Appalachians, while, in the Appalachian Mountains, Cambrian rocks are really much more extensive than the mere outcropping edges of the upturned strata. There is no reason, however, to think that the vast area of pre-Cambrian rock around Hudson Bay, the Atlantic Coast from New Jersey southward, and the Pacific Coast region from northern California northward through Alaska, were ever covered by Cambrian rocks.

The difference in the distribution of the Lower and Upper Cambrian strata is a prime consideration. Thus the Lower Cambrian is absent

FIG. 37. Structure section showing the folded Cambrian (*C*), Ordovician (*O*), Silurian (*S*), and Devonian (*D*) systems in the Appalachian Mountains of part of West Virginia. Length of section, 18 miles. (After Darton, U. S. Geological Survey.)

from the Interior Lowland and Great Plains regions. Otherwise the same general areas are occupied by both Lower and Upper Cambrian strata.

Description of the Rocks. Cambrian rocks consist very largely of shallow water sediments such as conglomerates, sandstones (Fig. 36), and shales, with well-preserved ripple marks very common. Deeper or clearer water deposits such as limestone, are, however, important in the Appalachians, Vermont, Nevada, the Rocky Mountain region, and British Columbia. When these sediments were deposited in the Cambrian sea they were like ordinary gravels, sands, marls, and limy oozes now forming in the ocean, especially over the continental shelf areas and their borders. Since their deposition they have been changed into the corresponding harder rocks such as conglomerates, sandstone, shales, and

limestones, or, in some cases as in New England and in the southern Appalachians, metamorphosed into quartzites, schists or slates, and marbles.

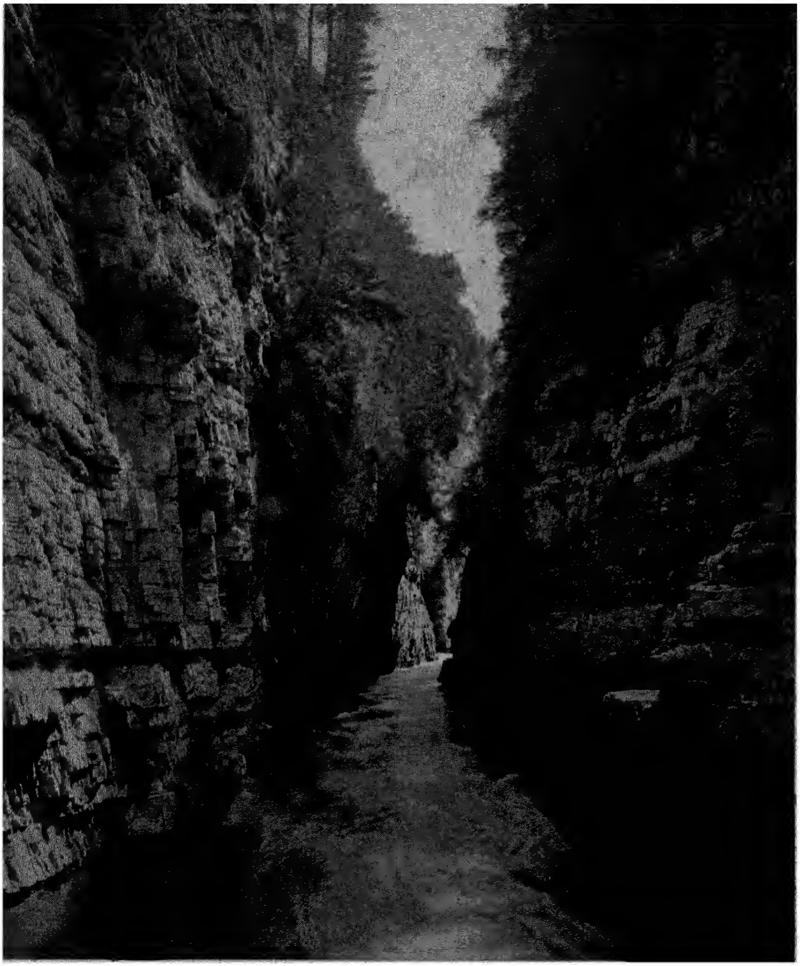


FIG. 38. Upper Cambrian (Potsdam) sandstone in the Ausable Chasm of northeastern New York. (Courtesy of the Ausable Chasm Company.)

In many regions the Cambrian strata have been highly folded and faulted, particularly in the Appalachian Mountains, New England, the Rocky Mountains, Utah, Nevada, and southeastern California.

North American Cambrian is singularly free from igneous rocks, and

it thus presents a remarkable contrast with the Proterozoic and Archeozoic systems in most regions.

The following statements will give a fair idea of the subdivisions, character, and thickness of the Cambrian system in widely separated parts of the United States. In eastern California (Inyo Mountains) the Cambrian is well represented, consisting of Lower Cambrian sandstone, shale, and limestone 10,000 feet thick overlain by 1000 feet of Middle Cambrian sandstone and limestone, and this in turn by about

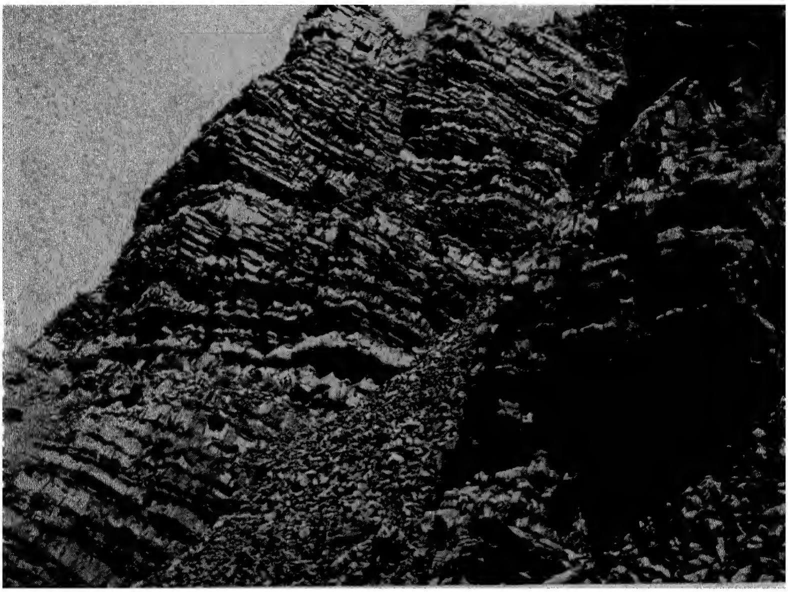


FIG. 39. Lower Cambrian strata at Deep Spring Valley, California.

1000 feet of Upper Cambrian limestone and shale, making a total thickness of 12,000 feet of Cambrian. At least as great a maximum thickness occurs in the Rocky Mountains of southern Canada and the northern United States where the Middle and Upper Cambrian strata (mostly limestone) are much thicker than they are in California. In Utah a thickness of 9000 feet of Cambrian is known.

In the southern Appalachian region Lower Cambrian sandstone and conglomerate reach a thickness of several thousand feet; Middle Cambrian limestone and shale, 3000 feet; and Upper Cambrian limestone and sandstone, 5000 feet.

Upper Cambrian rocks occur widely in the Mississippi Valley.

These are largely sandstones of widespread extent, and they are generally less than 1500 feet thick.

Physical History

Great Basal Unconformity. We have already learned that a profound and seemingly almost universal unconformity separates the Archeozoic and Proterozoic rocks. Another great unconformity separates the Proterozoic and Paleozoic rocks. Cambrian strata rarely if ever fail to rest upon the eroded surfaces of either the Archeozoic or the Proterozoic. C. D. Walcott stated in 1914 that no definitely proved transition rocks between the Cambrian and pre-Cambrian are known

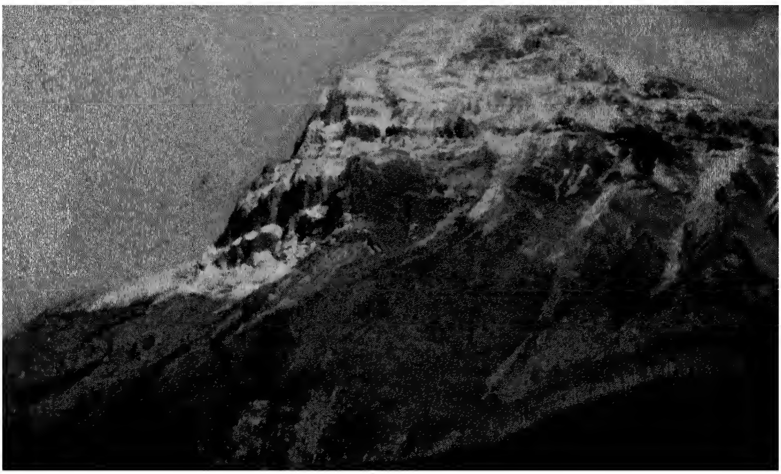


FIG. 40. Gently tilted Cambrian marine strata about one mile thick in Mt. Stephen, Canadian Rocky Mountains. (Courtesy of the Canadian Geological Survey.)

in North America. It has been definitely proved, as for example in the Adirondack region, to be quite the rule that the Cambrian sediments not only rest upon an eroded surface of older rocks, but that the surface of these latter had been worn down to the condition of a more or less well-developed peneplain. Accordingly, just before and during earliest Cambrian time, most, if not all, of North America must have been dry land undergoing erosion. Conglomerates containing pebbles of the older rocks are of very common occurrence at the base of the Cambrian sediments. The great duration of this erosion interval which produced such a profound unconformity, not only in North America but in other continents as well, is regarded as one of the greatest physi-

cal events of its kind in the history of the earth since the beginning of Paleozoic time.

Early and Middle Cambrian. During Early Cambrian time partial submergence of North America resulted in the development of two long narrow arms of the sea, one in the east and the other in the west,

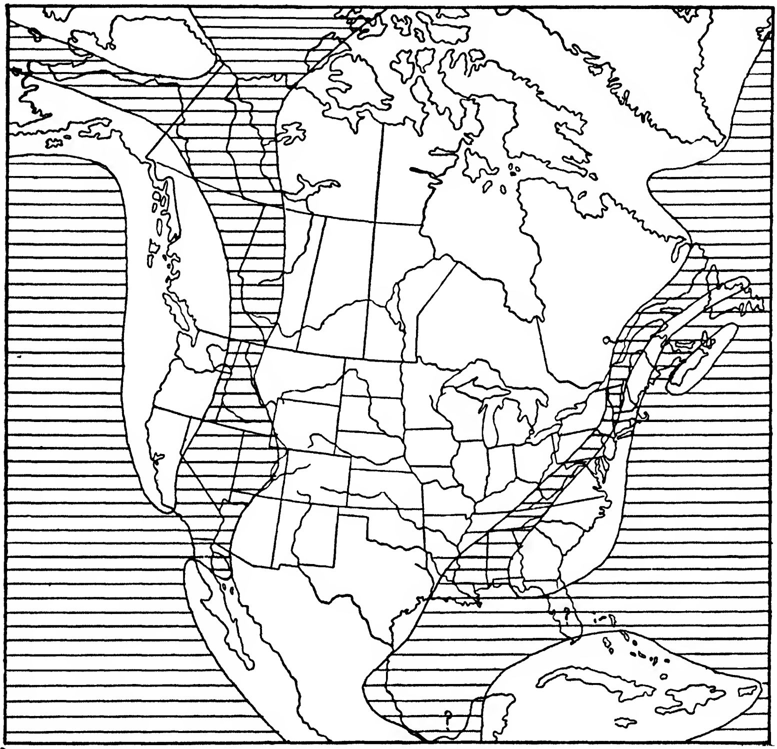


FIG. 41. Generalized paleogeographic map showing sea and land areas in North America during late Early Cambrian time. White areas, land; ruled areas, sea. Principal data (modified) from maps by B. Willis and C. Schuchert.

as shown on the accompanying map, Fig. 41. These marked the beginning of the Appalachian and Cordilleran geosynclines, respectively, which were more or less persistent during early and middle Paleozoic times. These seaways may have been produced either by rising sea level or subsidence of the land, or both. The Cordilleran sea encroached from both north and south, and the waters joined in the northern Idaho region in late Early Cambrian time. Rise of the sea was an important factor

because the development of the extensive peneplain surface above mentioned implies that the continent must have remained almost unaffected by diastrophic movements for a long time, and the tremendous volume of material removed and dumped into the sea must have very appreciably raised its level.

Wherever Lower Cambrian marine strata (actually exposed or concealed) rest directly upon pre-Cambrian rocks we can be sure that such areas were submerged under the Early Cambrian sea, because Lower Cambrian strata could have formed only during that time. To these areas must be added still others from which once present Lower Cambrian rocks have been removed by erosion. Again, many large areas were almost certainly dry land during Early Cambrian time because there is not the slightest evidence of any sort that deposition went on over those areas during that time. The principles here set forth are of fundamental importance in constructing a paleogeographic map of North America for Early Cambrian time, and the same principles must be kept in mind in considering the paleogeography of any given region during any succeeding time.

A considerable withdrawal of the eastern arm of the sea (especially in the north) marked the close of Early Cambrian time, but the western sea (or mediterranean) became somewhat larger, especially from Idaho eastward. This was the condition of the continent during Middle Cambrian time.

Late Cambrian. During Late Cambrian time more and more of the continent gradually became submerged until the geographic conditions were much as depicted upon the next paleogeographic map (Fig. 42). The sea transgressed northward over the great interior land to about the northern border of the United States, forming a vast interior sea. Fully one-third of the continent was flooded. As the map shows, there were six large land areas—Appalachia, Antillia, Canadia, Cascadia, Siouxia, and Mexicoia.[1] These six land areas, with somewhat changing borders, were remarkably persistent during the repeated early and middle Paleozoic flooding of the continent.

The northward transgression of this great interior sea in the eastern United States is clearly established by the fact that studies of actual outcrops and deep well sections show successively younger and younger Upper Cambrian sediments deposited by overlap northward upon the

[1] The term "Mexicoia" has been proposed by the author as a designation for the persistent Paleozoic land mass in the Mexican area.

pre-Cambrian rock surface. We also know that this interior sea was shallow because of the nature of the sediments which are very largely clastic such as sandstones and shales, often ripple marked, and with conglomerates at the base. Some heavy limestone beds like those in eastern

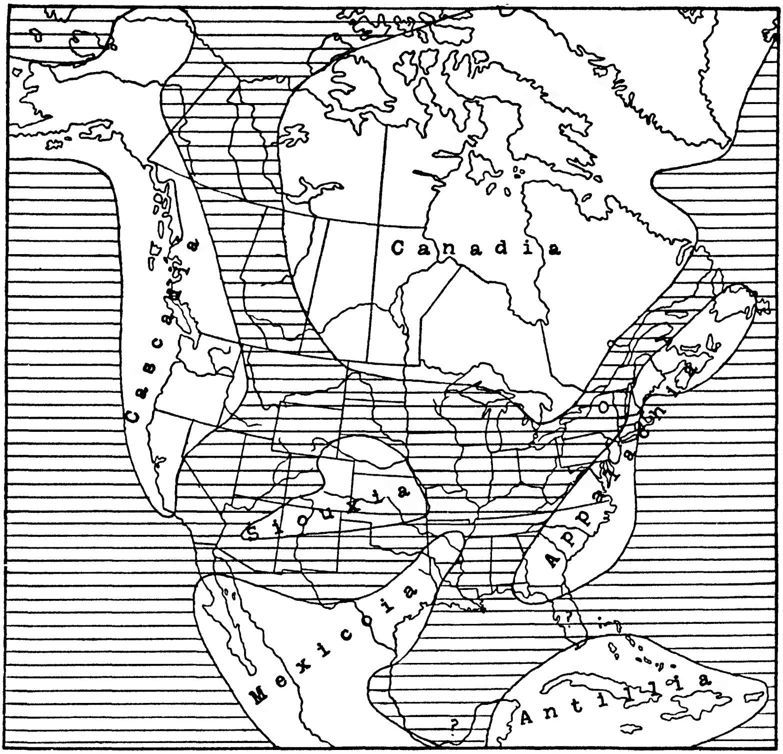


FIG. 42. Generalized paleogeographic map showing sea and land areas in North America during Late Cambrian time. This was the greatest Cambrian sea. White areas, land; ruled areas, sea. Principal data (modified) from maps by B. Willis and C. Schuchert.

New York, and between Virginia and Missouri, tell of clearer, possibly deeper, water in those places.

Close of the Cambrian. Throughout Cambrian time, and even at its close, North America was not affected by any really great physical disturbances such as mountain-making or igneous activity.

According to Schuchert the Cambrian period closed with "a very wide and probably complete retreat of the epeiric (continental) seas

from the interior parts of North America, leaving the continent all or nearly all dry land." Millions of years of erosion during Cambrian time, when the continent was remarkably stable, reduced the land areas to low levels with little relief. Gentle emergence at the close of the period brought the widespread Late Cambrian strata but little above sea level. Thus the whole continent was a low, remarkably flat land area at the close of the Cambrian. Erosion was, therefore, very slow and but little of the Cambrian material was removed before being covered largely by the Early Ordovician sea (Fig. 48).

Climate

We have already learned that comparatively high lands, with accompanying glaciation, marked the closing stages of the Proterozoic era in many parts of the world. Very early in the Cambrian period, however, the lands were generally lower, and glacial conditions no longer existed.

The character and widespread distribution of many of the organisms of the time (especially those which secreted lime from sea water) throughout low and high latitudes, and also the conditions favorable for ordinary processes of weathering, erosion, and deposition of sediments, indicate that the climate of Cambrian time was not essentially different from that of comparatively recent geological time, but that climatic conditions were then much more uniform over the earth than now. Considerable limestone formations of Cambrian age at high latitudes indicate strongly that they were there deposited in relatively warm or temperate waters.

Economic Products

Cambrian rocks, such as the Potsdam sandstone and Little Falls dolomite in New York, furnish considerable quantities of building stone.

Cambrian sandstone outcropping extensively in southern Wisconsin and through the Appalachian region is used as building stone and for other purposes.

Roofing and other slates of Cambrian age are quarried in the metamorphic rocks of the eastern United States, especially in eastern New York, southwestern Vermont, and Maine.

Important lead deposits occur in the Cambrian limestone of southeastern Missouri. Copper deposits occur in Cambrian rocks in western North Carolina and southeastern Tennessee.

Some gold, originally laid down in the form of placer deposits, occurs in Cambrian conglomerate in the Black Hills of South Dakota.

Foreign Cambrian

Europe.—Like that of North America, the Cambrian rocks of Europe generally rest upon the profoundly eroded surface of either Proterozoic or Archean rocks. The physical geography of the continent, however, differed considerably because the distribution of the rocks shows that the Early Cambrian sea was almost wholly limited to northern Europe, while the Middle Cambrian sea transgressed farthest over much of France, Germany, Bohemia, Spain, and Sardinia, and in the Late Cambrian the sea spread widely over Europe, as shown by the distribution of Late Cambrian marine strata.

In Wales and Britanny the Cambrian strata appear to have a maximum thickness variously estimated at from 12,000 to 20,000 feet, while in southern Sweden the whole Cambrian is only about 400 feet thick. Like those of North America, the rocks are mainly clastic sediments of shallow water origin such as conglomerates, sandstones, and shales. In western Europe, for example in Wales and southern Scandinavia, the Cambrian strata are thoroughly indurated and usually highly folded, but in eastern and central Europe, for example in Russia, most of the strata are practically horizontal, and even unconsolidated beds of sand and clay have been found. Unconsolidated beds of such great age are truly remarkable, an important exception being in Wales.

The Cambrian period closed in Europe without any important physical disturbance.

Other Continents.—The Cambrian of other continents has generally not been well studied, but rocks of this age are known in Australia, Tasmania, India, China, Korea, Siberia, and Argentina. Only slightly folded or tilted strata of Cambrian age up to 20,000 feet thick are known in northern China.

CHAPTER X

ROCKS AND PHYSICAL HISTORY OF THE ORDOVICIAN

Origin of Name and Subdivisions

In the preceding chapter we learned how the basal portion of Murchison's great Silurian system came to be called the Cambrian. In 1879 Lapworth proposed to divide the remaining Silurian system into two parts, the lower portion to be called Ordovician, and the upper to retain the name Silurian. The term Ordovician was taken from an old tribe (Ordovici) which once inhabited Wales. When it is realized that one of the most profound stratigraphic breaks (unconformities) in the whole Paleozoic group lies within Murchison's old Silurian system, and between what are now called the Ordovician and Silurian systems, the justification of Lapworth's proposal is evident. In America and England the Ordovician system is now generally recognized, though on the continent of Europe the term Lower Silurian is still largely employed instead. The following tabular arrangement will serve to make clear the history of these terms:

	(*Murchison, 1835*)	(*Sedgwick*)	(*Lapworth, 1879*)
Silurian System	Upper Silurian	Upper Silurian	Silurian
	Lower Silurian	Lower Silurian	Ordovician
		Cambrian	Cambrian

Since the North American Ordovician was first carefully studied in New York state, the section there has become, to a very considerable degree, the standard to which the subdivisions in other parts of the continent are referred. During recent years several unconformities, though rather minor ones, have been discovered in the New York Ordovician, so that this section is not as perfect or continuous (stratigraphically) as was formerly supposed, certain records being entirely missing. Following are the principal divisions of the Ordovician system, with formation subdivisions in two well-known regions, as they are recognized in North America:

General	*New York*	*Upper Miss. Valley*
CINCINNATIAN (Upper Ordovician)	Queenston sh.[1] Oswego ss. Pulaski sh. Frankfort sh. Utica sh.	Maquoketa sh. Maysville fm. Eden sh.
CHAMPLAINIAN (Middle Ordovician)	Trenton ls. and Canajoharie sh. Black River ls. Chazy ls.	Galena ls. Decorah sh. Platteville ls. St. Peter ss.
CANADIAN (Lower Ordovician)	Beekmantown ls. Tribes Hill ls.	Shakopee dol. Oneota dol.

1 In this and succeeding tables abbreviations have the following meanings: Shale (sh.), sandstone (ss.), conglomerate (cg.), limestone (ls.), and formation (fm.) where one kind of rock is not distinctly predominant.

The reader should not be led to think that the above listed formation or stage names are the only ones now used in North America. Many other, more or less local, names have been applied either to formations (stages) found elsewhere but missing in New York, or to formations which have not yet been definitely correlated with those of New York. It is generally agreed, on the basis of priority, that when two widely separated formations become definitely correlated, the name given the formation where first studied is to be applied to both. In this way many of the New York names have come to be used over wider and wider areas. Also the kind of rock (lithologic character) making up a formation in New York may or may not be the same in other areas. Thus a sandstone or shale in New York may be replaced by a shale or limestone elsewhere, etc.

In New York, and usually elsewhere, the Ordovician strata, especially the Middle and Upper, and more especially the Trenton beds, are wonderfully rich in organic remains, and much attention has been given to the description of the fossils and the correlation of the strata. Unconformities within the Ordovician system are, relatively speaking, not very common, and they are usually not very profound. There are, however, two widespread unconformities, each representing an extensive, though short interval of withdrawal of marine waters during the period.

DISTRIBUTION AND DESCRIPTION OF THE ROCKS

General Distribution. Most of the regions indicated in black in Figure 36 contain large or small areas of outcrops of Ordovician strata, thus showing the remarkably widespread surface distribution of strata

of this age. It is also a significant fact that most of the widely distributed Ordovician strata by far were laid down under sea water.

The surface distribution of Cambrian and Ordovician strata is much the same except for the presence of Ordovician and lack of Cambrian in the Arctic Islands, Hudson Bay region, and the large area southwest of Hudson Bay.

As in the case of the Cambrian, so the surface distribution of the Ordovician rocks as indicated on this map gives no adequate idea of the former or present real extent of strata of this age, since strata have either been removed from so many districts by erosion or are concealed under later formations, or are highly folded so that outcropping edges only are at present visible in comparatively narrow belts following the strike of the folds.

Some regions can quite certainly be shown to have been formerly covered by Ordovician strata, as, for instance, nearly all of the Adirondack Mountain region of pre-Cambrian rocks (Fig. 43), and a wide area between the Great Lakes and Hudson Bay. Also the distribution of the outcrops, together with numerous deep-well sections or records, conclusively prove that much of the Mississippi Basin contains concealed Ordovician rocks.

Description of the Rocks. Viewed in a broad way, the Ordovician rocks (especially the Lower and Middle) are of different nature from those of the Cambrian. Clastic sediments, such as conglomerates, sandstones, and shales, are the dominant Cambrian sediments, while, throughout the Lower and Middle Ordovician, limestones greatly predominate (Fig. 44).

As will be explained, North America, as well as other parts of the northern hemisphere, were largely submerged under shallow seas during much of Ordovician time. The nature and distribution of the fossils in these rocks show that the temperature of these seas was mild and remarkably uniform, probably because ocean currents then had much freer play than they do today thus tending to keep the temperatures of northern and southern latitude seas more uniform. Because the lands were generally small and low, comparatively little land-derived sediment was carried into the seas. The Ordovician seas were, therefore, remarkably favorable for the growth of countless myriads of lime-secreting organisms with resultant very widespread accumulation of limestone formations.

Of the Lower Ordovician formations in eastern North America, the *Beekmantown* is one of the most widespread. It is extensively developed

in New York and in the Appalachian region. It is usually a dolomitic limestone. Lower Ordovician limestone also occurs extensively in the

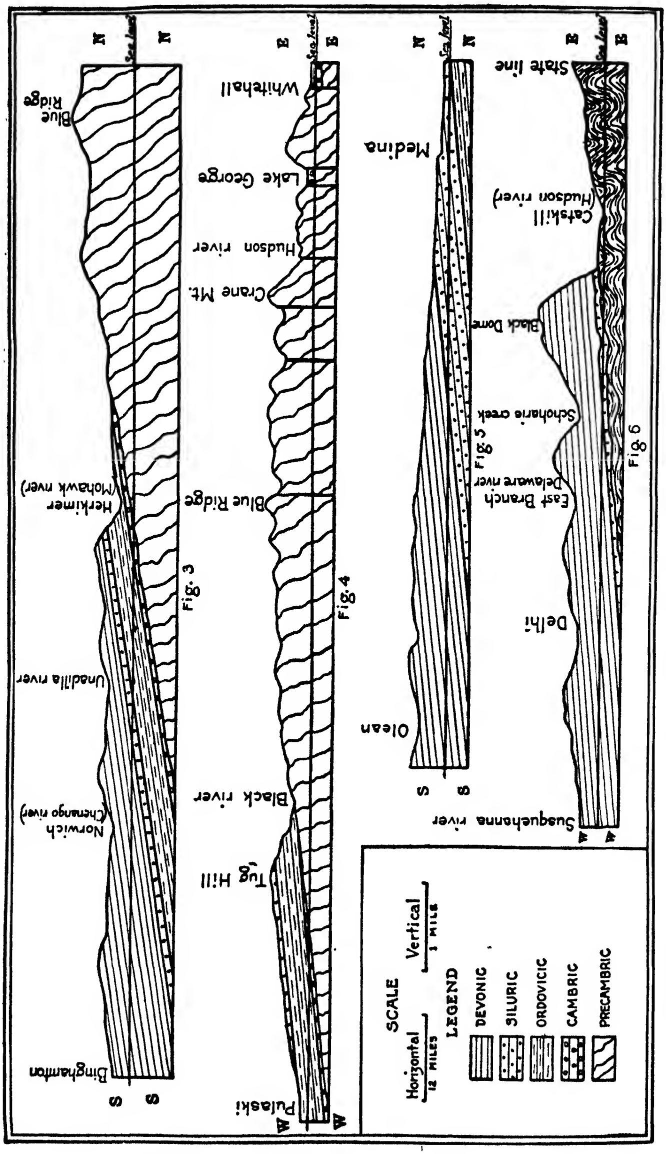


Fig. 43. Generalized structure sections through various parts of New York State, showing the attitude and relations of the various great rock systems. (After W. J. Miller, *N. Y. State Mus. Bul. 168.*)

mountains of Oklahoma, the Interior Lowland, and mountains of the western United States.

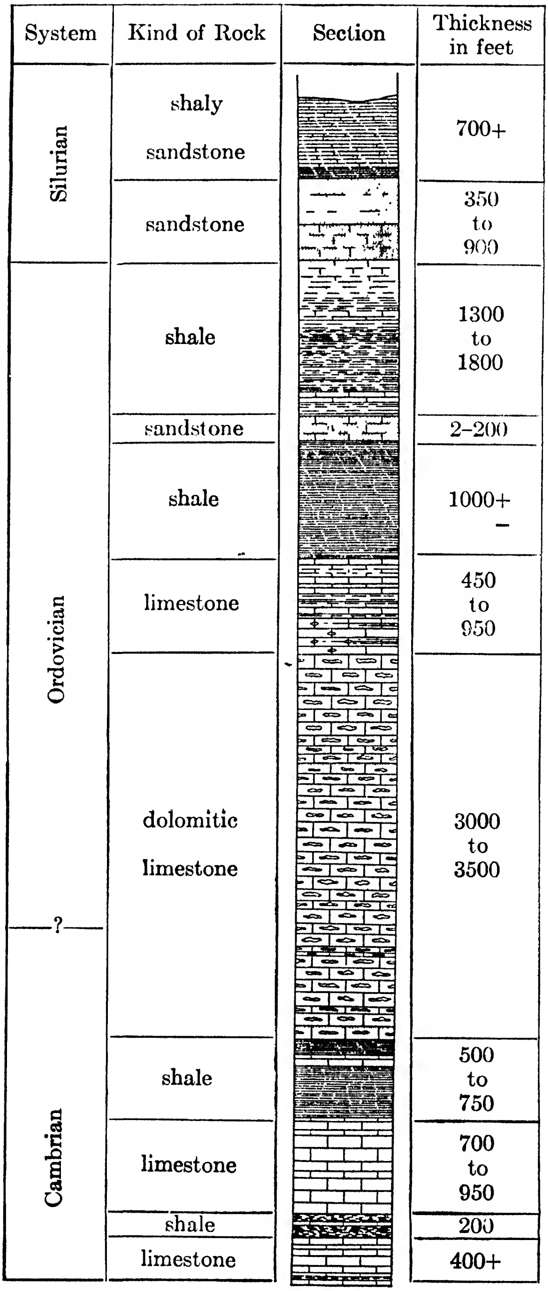


FIG. 44. Geologic (columnar) section in eastern Tennessee, showing the predominance of limestone in the Lower and Middle Ordovician, and of shale and sandstone in the Upper Ordovician. (After Keith, U. S. Geological Survey, Folio 118.)

Mid-Ordovician is generally regarded as having been one of the greatest limestone-making times in the earth's history, though it should not be inferred that limestones were then universally made in the seas, because those areas of deposition close to, or receiving wash from, the lands show clastic sediments. Middle Ordovician, especially Trenton, limestones are remarkably widespread, occurring in New York, New England, New Brunswick, southeastern Canada, near Hudson Bay, across the northern part of the Mississippi Basin, Black Hills, Wasatch and Uinta Mountains, and even in the Great Basin.

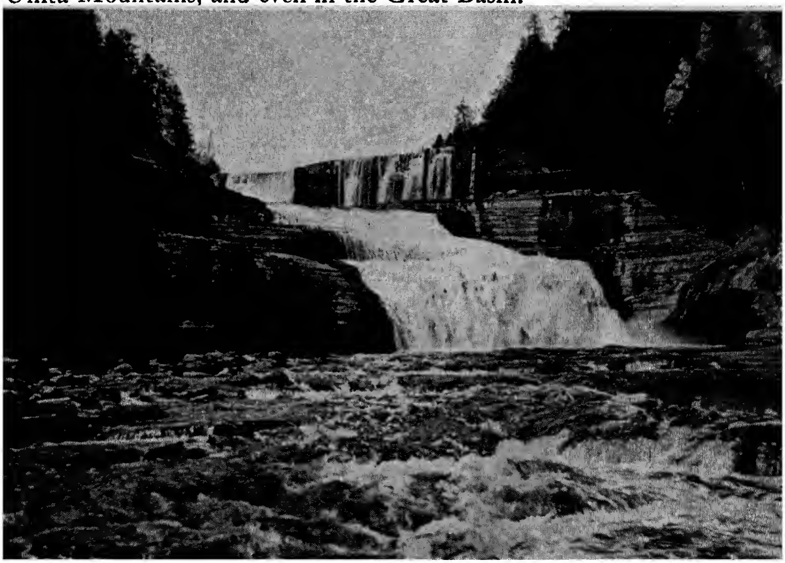


FIG. 45. The Trenton (mid-Ordovician) limestone at its type locality, Trenton Falls, New York. (Photo by F. B. Guth, Utica, N. Y.)

The *Trenton* limestone may be specially mentioned as a remarkable example of a relatively thin formation of very great extent. It is seldom more than 500 feet thick; it consists very largely of highly fossiliferous marine limestone; and it once existed as a single, unbroken sheet of rock over an area of several hundred thousand square miles of the New York-Appalachian Mountain-Interior Lowland region. Much of the original rock is still left at the surface or under cover of later rocks.

An illustration of an exception to universal limestone-making during Trenton time is the Mohawk Valley region of New York where the limestone passing eastward gives way almost wholly to a formation of shale hundreds of feet thick, known as the *Canajoharie* shale. Also

through the Appalachians rocks of mid-Ordovician age contain more or less clastic material.

In the Upper Ordovician of eastern North America shales and alternating shales and fine-grained sandstones (e.g. *Utica* and *Frankfort*) greatly predominate, doubtless due to rejuvenation and more active erosion of the lands probably accompanied by some shoaling of the water.

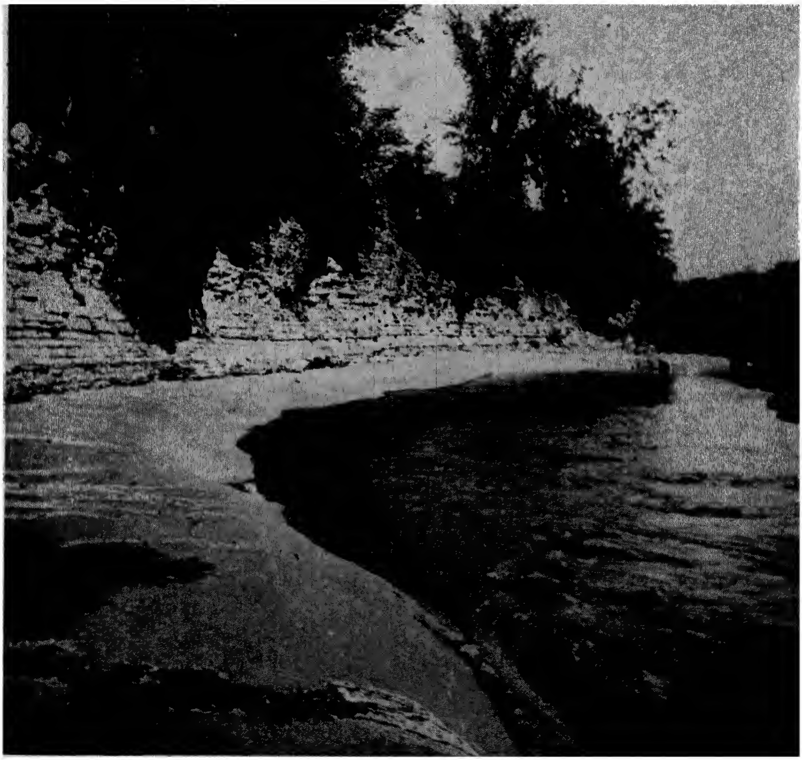


FIG. 46. Trenton limestone (thin-bedded) resting upon massive Black River limestone near Boonville, New York. Both formations contain many fossils.

In the western part of the continent, the Ordovician system, including much limestone, outcrops in various parts of the Rocky Mountains, the Basin and Range Province, and California. The rocks are a good deal like those of the east, but the sections are usually less complete and less well-studied. In the Inyo Mountains of eastern California there are 5,000 feet of marine strata, largely limestone.

The aggregate thickness of Ordovician strata in New York is from

2000 to 4000 feet; in the Appalachian Mountains, 5000 to 8000 feet; in the central Mississippi Valley (i.e. Missouri), 1000 feet or less; in the Arbuckle Mountains of Oklahoma, 10,000 feet; in the Rocky Mountains, several thousand feet; and in eastern California, 5000 feet.

The Ordovician strata in New England, the Appalachian Mountains (Fig. 37), the mountains of Oklahoma, the Rocky Mountains, Utah, and the Basin and Range Province are usually more or less highly folded and faulted. Elsewhere, as throughout the great Interior Lowland, they are but little disturbed from their original horizontal position.

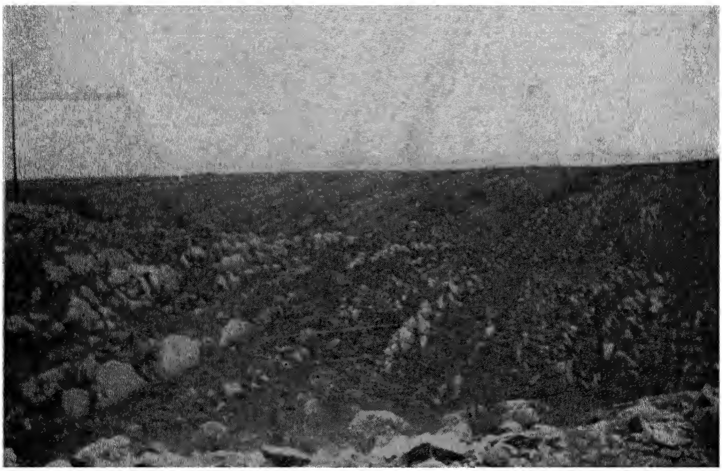


FIG. 47. Outcropping edges of deeply eroded, nearly vertical, Cambro-Ordovician strata in the Arbuckle Mountain region near Ardmore, Oklahoma. (Photo by K. Zercher.)

In parts of New England and the western United States, Ordovician strata are often notably metamorphosed.

Igneous rocks are sparingly represented in the Ordovician system of North America. Plutonic rocks are practically unknown, but a remarkable occurrence is that of several thin beds of Middle Ordovician volcanic ash within an area of several hundred thousand square miles of the Appalachian region and eastern Interior Lowland. Middle Ordovician volcanic rocks occur in Newfoundland, in a part of eastern Quebec, and in parts of Alaska.

Physical History

Early Ordovician. After the extensive emergence which caused practically all of North America to be a land area at the close of the

Cambrian, the sea began, in Early Ordovician time, to encroach upon portions of the continent. By the middle of the Early Ordovician, marine waters overspread much of the Rocky Mountain region, with Arctic and Pacific Ocean connections, the latter through Nevada and southern California; an arm of the sea extended over the Appalachian Mountain-St. Lawrence Valley areas, connecting the Gulf of Mexico

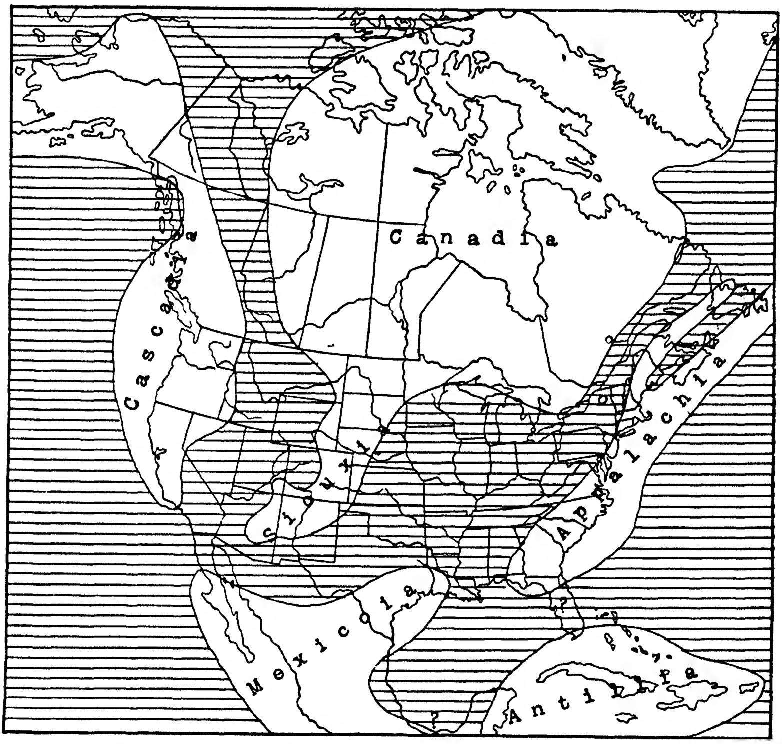


FIG. 48. Generalized paleogeographic map showing sea and land areas in North America during Early Ordovician time. White areas, land; ruled areas, sea. Principal data (modified) from maps by C. Schuchert and A. Grabau.

with the Gulf of St. Lawrence and overspreading the eastern one-half of the Mississippi Basin area; and the western and eastern seas were probably connected across the southwestern United States. Cascadia, Appalachia, Antillia, and Mexicoia were well-defined land areas, as they usually were during the greater Paleozoic floods, but Canadia was very large, extending far southwestward in the United States to Arizona, thus including Siouxia. Map Fig. 48 shows the relations of land and sea at that time.

Early (or Lower) Ordovician time seems to have closed with a general disappearance of the marine waters from North America.

Middle Ordovician. Middle Ordovician time was marked by a still greater invasion of the continent by marine waters. Beginning with a generally emergent continent the waters spread until a climax was reached when not only the Early Ordovician marine areas were again submerged, but also more of Canadia especially in the Arctic Islands region. The lands were low, erosion was not very active, the seas were wide, and, therefore, relatively little land-derived sediment was deposited on the floor of the extensive continental sea. It was a time unusually favorable for limestone making, and the remarkably extensive Trenton limestone was then formed. This sea teemed with invertebrate forms of life, including thousands of species of lime-secreting organisms.

In sharp contrast to a general lack of diastrophism, involving important folding, faulting, or igneous activity, was the explosive activity of some volcanoes in the Appalachian region, causing beds of volcanic ash, varying from 1 to 10 feet thick, to be deposited over much of the eastern United States. Vigorous volcanic activity occurred in Newfoundland, in a part of eastern Quebec, and in parts of Alaska.

Middle Ordovician time was brought to a close by a withdrawal of the great sea from practically all of the continent.

Late Ordovician. Late Ordovician time was marked by the most extensive transgression of the sea in the known history of the continent. This sea covered not only the same general areas as the Early and Middle Ordovician seas, but also more of Canadia as shown by Figure 49. Waters from the Arctic, Pacific, Atlantic, and Gulf of Mexico all took part in the development of this vast epeiric sea.

The spread of the Ordovician seas repeatedly over so much of the continent is more readily understood when it is realized that the lands were generally low and featureless so that relatively little change of level between sea and land allowed extensive marine invasions.

Because Late Ordovician sediments of the eastern United States are prevailingly clastic (sandstones and shales), it is evident that an important change in physical geography conditions took place there late in the period. The clastic sediments came from the east as proved by their distribution. This shows that Appalachia, their source region, underwent notable rejuvenation well before the close of the period, and that the relatively higher old-land was eroded fast enough to supply much clastic sediment.

As we shall learn presently, important crustal disturbances (orogenic), accompanied by uplifts, reached their climax just west of middle Appalachia toward the close of the period.

As a result of general emergence, the vast sea was expelled, and practically the whole continent was dry land at the close of the Ordovician period. Thus, three times during this one period, seas advanced over, and retreated from, extensive portions of North America.

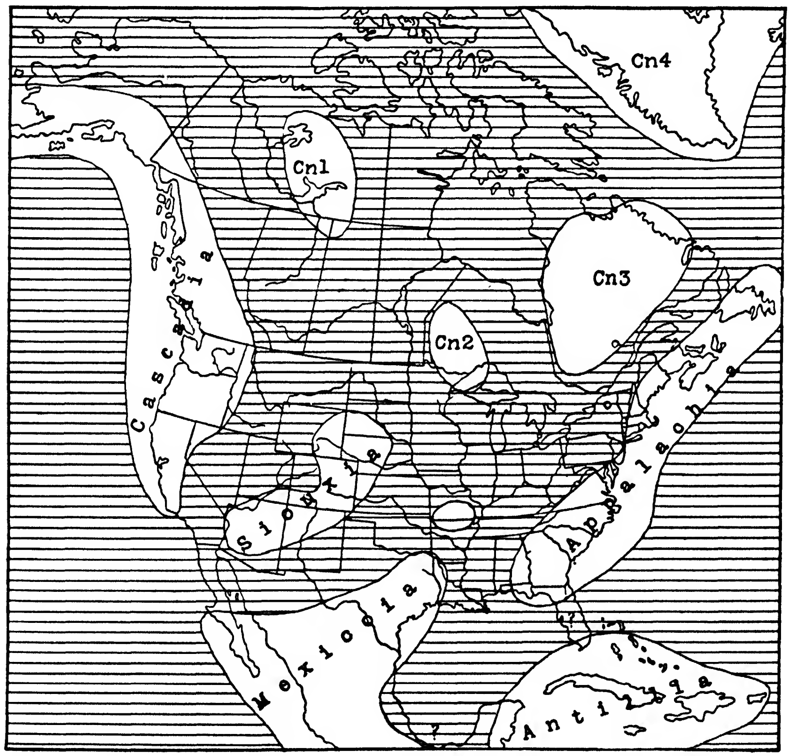


FIG. 49. Generalized paleogeographic map showing sea and land areas in North America during Late Ordovician time. This was the most extensive known sea in the history of the continent. White areas, land; ruled areas, sea. Cn 1, 2, 3 are parts of Canadia. Principal data (modified) from maps by B. Willis, C. Schuchert, and R. Chamberlin.

Depth of Ordovician Seas. Because Ordovician strata often show a thickness of 2000 to 8000 feet, it should not be inferred that the Ordovician sea was necessarily ever 2000 to 8000 feet deep. The strata, even

including limestones, often abundantly prove by ripple marks, mud cracks, and character of the fossils that they were laid down in shallow sea-water. The very character of the thick materials (original muds and sands) in the Upper Ordovician implies that they could not have been deposited in deep ocean water. Such sediments are not now forming on the deep-sea bottom. How are these statements to be harmonized with the fact that Ordovician strata thousands of feet thick exist over considerable areas? During long portions of the period the sea bottom more or less gradually subsided while stratum after stratum was deposited, and so it is not necessary to assume that the water was ever really deep. The usual depth was probably not over several hundred feet, while a depth of 1000 feet rarely if ever obtained. The North American oceans were, in other words, true epicontinental (or epeiric) seas. There were no ocean abysses at all comparable to those of the present Atlantic or Pacific where depths of three to five miles are common. This is known because no true deep-sea deposits occur in the Ordovician. The principles here set forth are applicable also to the continental seas of other periods of geological time.

Close of the Ordovician (Taconic Revolution).—The Ordovician ended with important physical or crustal disturbances, including mountain-making. All, or nearly all, of the great interior (epeiric) sea appears to have been drained as a result of change in level between land and sea in late Upper Ordovician time. In the interior of the continent the land was only moderately elevated to remain dry until the early part of the next period.

Thousands of feet of Cambrian and Ordovician strata accumulated in the seas which covered eastern New York, the sites of the Green Mountains and Berkshire Hills of western New England, eastern Pennsylvania, and possibly as far south as northern Virginia, including part of the Piedmont Plateau area. Toward the close of the Ordovician period, a great compressive force was brought to bear in the earth's crust upon this mass of strata. As a result of the orogeny, the strata were folded, probably thrust-faulted, and elevated into a mountain range which has been called the Taconic Range, and the physical (orogenic) disturbance has been called the *Taconic Revolution.* In structure, the range consisted of a series of folds, both great and small, whose axes were parallel to the main axis of the range, that is, north-northeast by south-southwest. Though we have no way of telling just how high the range may have been, nevertheless the structural features and the vast amount of erosion

since the folds were produced clearly indicate that the uplift was at least some thousands of feet.

In passing westward from the main axis of the range, the folding is less and less intense, till finally the folds die out altogether.

How do we know that the Taconic disturbance took place toward the close of the Ordovician period? Strata of the next succeeding period (Silurian) rest directly in places upon the eroded edges of Late Ordovician rocks; hence it is obvious that the disturbance occurred before the Silurian strata were deposited (Fig. 50). Also the disturbance doubtless began before the close of the Ordovician period. This is borne out by the fact that, for example, in central New York a distinct eroded surface at the summit of the Frankfort shales proves that region to have been dry land before the end of the period, this uplift quite certainly

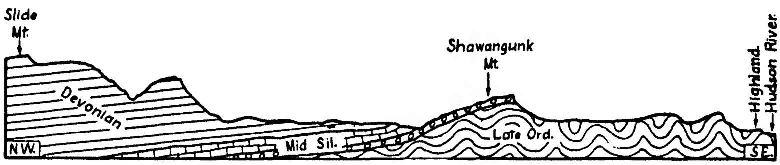


FIG. 50. Structure section through part of southeastern New York showing how the Late Ordovician strata were folded (Taconic Revolution) and eroded before the Silurian strata were laid down nonconformably upon them. The Silurian strata were deformed at a much later time.

having been produced by the early movements of the Taconic Revolution.

In New Brunswick, Silurian strata rest upon the eroded edges of upturned Ordovician strata, and this upturning may have been coincident with the Taconic disturbance.

Sufficient upwarping occurred in a portion of the Mississippi Basin, during the latter part of the period, to produce a long, very low arch in the rocks from northern Ohio to central Tennessee. This has been called the "Cincinnati Anticline."

CLIMATE

Red sandstones, salt, and gypsum in the Upper Ordovician of northern Siberia clearly imply an arid climate in northern Asia during the late Ordovician. So far as can be determined from the character of the rocks, geographic conditions, and distribution of the fossils, the climate of North America and Europe must have been mild and much more uniform than now. Ordovician fossils even from Arctic lands, are very similar to those of low latitudes.

The very extensive Ordovician seas, allowing a much freer circulation of waters between low and high latitudes, no doubt helped to keep the climate of the earth more uniform then than at the present time.

Economic Products

Great quantities of Ordovician limestone are quarried for building purposes or burnt for lime in various parts of the United States. Great quantities of Ordovician marble are quarried in western New England, especially in Vermont near Rutland and Proctor. Other important quarries are in eastern Tennessee.

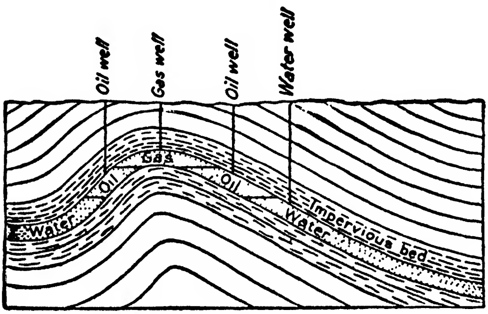


FIG. 51. Structure section to show a typical occurrence of gas, oil, and water in an anticlinal structure. (After U. S. Geological Survey.)

In eastern Pennsylvania much Trenton limestone is used in making Portland cement.

Much Ordovician slate is quarried from southern Vermont to Virginia.

The St. Peter sandstone of the upper Mississippi Valley is an important aquifer. It is also much used in the manufacture of glass.

Important lead and zinc ores occur in Ordovician limestones in Wisconsin, Illinois, and Iowa.

Manganese ores of Arkansas and phosphate deposits of Tennessee occur in limestones of this age.

Oil and gas in the Ohio-Indiana field (Fig. 52) are derived largely from Ordovician rocks, especially the Trenton limestone. In the great Mid-Continent field of Kansas and Oklahoma, large quantities of oil are obtained from Ordovician sandstones. Two of the greatest districts —Seminole and Oklahoma City—have each produced hundreds of millions of barrels of oil.

In most cases by far oil and gas occur in porous beds or formations (usually sandstone) lying between impervious beds (usually shale). Most typically the gas and oil are arranged in order of specific gravity along the axis and upper flanks of anticlinal structures, with water usually at still lower levels (Fig. 51). The oil and gas were formed by decomposition of rich organic accumulations in the strata.

FOREIGN ORDOVICIAN

Ordovician marine strata are widespread in Europe, and there, as in North America, shallow seas, teeming with life, covered large parts of the continent much of the time. There were two distinct provinces, a northern and a southern, as proved by important differences between the fossils of northern and southern Europe. The Ordovician fossils of northern Europe are closely related to those of North America, thus implying a shallow sea connection between North America and Europe.

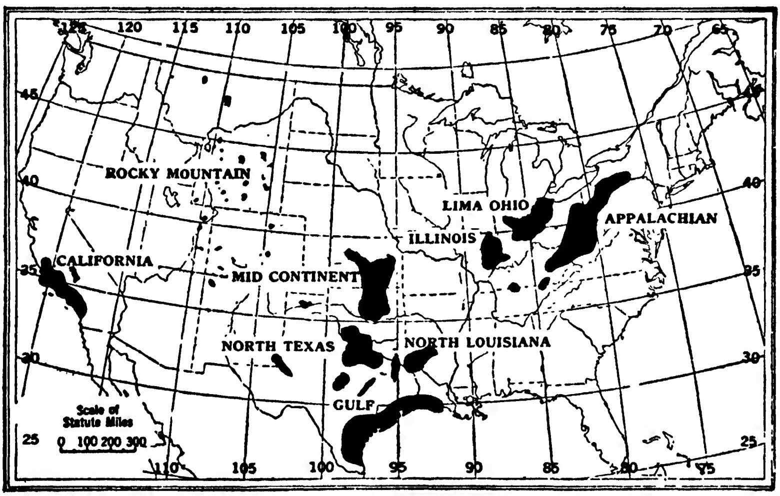


FIG. 52. Map showing the principal oil fields of the United States. (Modified after Geological Survey of Kansas.)

The scarcity of limestone in the European Ordovician is in marked contrast with that of North America.

In the British Isles, where the European Ordovician is thickest (being many thousands of feet), great igneous intrusions and extrusions took place, so that this region ranks as one of the greatest ancient volcanic areas in Europe.

As in North America, important geographic changes took place toward the close of the period, and the Silurian often rests by unconformity upon the Ordovician. In the British Isles the Ordovician rocks were folded, upraised, and often metamorphosed, with Silurian strata resting upon their eroded edges.

Ordovician rocks are also known in Peru, Argentina, Australia, Tasmania, New Zealand, Africa, India, eastern China, and northern Siberia.

CHAPTER XI

ROCKS AND PHYSICAL HISTORY OF THE SILURIAN

Origin of Name and Subdivisions

We have already learned how the great body of lowest fossiliferous strata in the British Isles was called the Silurian system by Murchison in 1835. The name was derived from Silures, an old tribe which once lived in part of Wales. In the preceding chapter we have also shown how the Silurian has since been divided into three systems—Cambrian, Ordovician, and Silurian. In view of the priority of Murchison's term "Silurian," and the fact that the Ordovician strata are now known to be more important and widespread than those we call Silurian, it seems inappropriate that the terms Ordovician and Silurian are not employed in the reverse order.

Since the Silurian strata in this country, too, were first carefully studied in New York, the section for that state becomes to a very considerable degree a standard of comparison for all American Silurian strata. Like the Cambrian and Ordovician systems, the Silurian is generally subdivided into three major portions or series, these in turn being subdivided into various stages.

Following are the principal divisions of the Silurian system, with subdivisions in three well-known regions, as they are recognized in eastern North America:

General	*New York*	*Virginia*	*Iowa*
Cayugan (Upper Silurian)	Manlius ls. Rondout ls. Cobleskill ls. Salina fm. (with salt)	Tonoloway ls. Wills Creek sh. McKenzie fm.	Salina fm.
Niagaran (Middle Silurian)	Guelph dol. Lockport dol. Clinton fm. (with iron ore)	. . . . Rochester sh. Rose Hill fm.	Bertram dol. Gower dol. Hopkinton dol.
Medinan (Lower Silurian)	Albion ss., Oneida (Shawangunk) cg.	Tuscarora ss.	Waucoma ls. Winston dol.

The classic New York Silurian section is more complete than the Ordovician, because the unconformities are fewer and of lesser importance, so that few horizons are missing. As was stated in connection with the Ordovician, so here, it should be remembered that many formation or stage names have been more or less locally applied in North America to formations not yet definitely correlated with those of New York, or to a few others not represented in New York. Also the lithologic character of formations may be quite different in different regions.

Distribution and Description of the Rocks

General Distribution. As in the case of the Ordovician system, most of the regions indicated in black in Figure 36 contain large or small areas of outcrops of Silurian strata, thus showing their remarkably widespread surface distribution. Most of the areas of outcrops by far lie in the eastern one-half of North America, mainly in the Appalachian Mountain, Interior Lowland, New York, Great Lakes, Gulf of St. Lawrence, Hudson Bay, and Arctic Islands regions. Comparatively few, small, scattered areas occur from the Rocky Mountains westward. Certain points of comparison with the distribution of the Ordovician may be mentioned. Thus to a very considerable degree the Silurian and Ordovician rocks occur in the same areas, the chief differences being much more extensive areas of Silurian strata in the Arctic Islands region, their almost complete absence from the upper St. Lawrence Valley, and their much smaller representation in the mid-Mississippi Basin, Rocky Mountains, and Great Basin of the west.

As stated in connection with the two preceding areal distribution maps, so here, the surface distribution of Silurian rocks by no means indicates the former or even present actual extent of these rocks in North America. From many regions Silurian strata have been removed by erosion, while in other regions they are concealed under cover of later rocks. Thus most of the upper Mississippi Basin, with its essentially horizontal strata, is underlain with Silurian rocks, and only the eroded edges of upturned Silurian strata are exposed in the Appalachian Mountains.

Silurian Strata in the East. *Medinan Series.* This series is represented by the *Albion* formation in western New York, being excellently exposed in Niagara Gorge. It consists of various strata such as alternating layers of cross bedded greenish and reddish sandstones and shales together with some beds of impure limestone.

The (Medinan) *Oneida* conglomerate occurs in central New York. Ripple marks, cross bedding, and the character of the fossils prove that the Oneida was laid down in a very shallow (probably encroaching) sea. It contains numerous well-rounded pebbles in a matrix of coarse sandstone. It rests upon the eroded edges of Upper Ordovician shales.

The *Shawangunk* conglomerate (Fig. 53) is very similar to the Oneida in age and composition, but it is much thicker (hundreds of feet). The eroded edges of its resistant, tilted beds forms the Shawangunk Ridge of southeastern New York and the Kittatinny Ridge of New Jersey and eastern Pennsylvania where it rests upon the eroded edges of

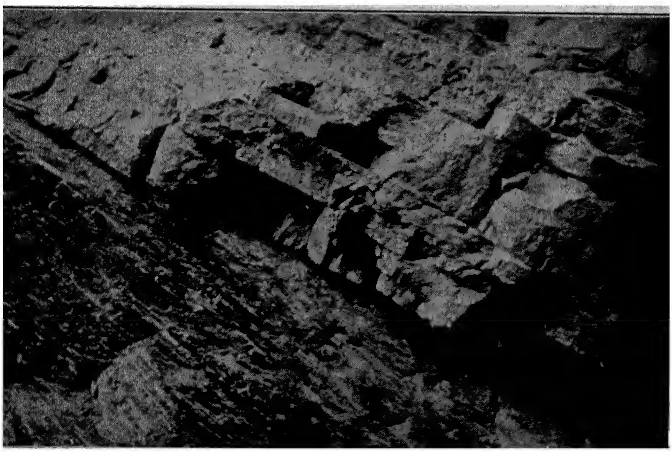


FIG. 53. Lower Silurian (Shawangunk) conglomerate resting by unconformity upon Upper Ordovician shale near Otisville, New York. (After New York State Museum.)

folded Ordovician shales. The Delaware River has cut the famous Delaware Water Gap through this formation. Continuing southward through the Appalachian region, a formation of the same age is known as the *Tuscarora* sandstone. In the Interior Lowland, Medinan rocks are mainly limestones. The coarse Medinan sediments just described resulted from vigorous erosion of the newly formed Taconic Mountains or rejuvenated Appalachia, or both, to the cast.

Niagaran Series. The *Clinton* formation and its correlatives, extends through the Appalachian Mountains, westward from central New York to Lake Huron and Indiana into Wisconsin, and probably through Illinois and Missouri. It is also known in Nova Scotia. Lithologically this formation is quite variable, being mostly shales and sandstones in

the Appalachians and central New York, and largely limestone in western New York and farther west and southwest. This limestone does not imply deep marine water, but merely shallow water comparatively free from land-derived sediments. A remarkable and very common feature of the Clinton formation is its interstratified beds of iron ore (hematite). This iron ore is especially well developed throughout the Appalachians, from central to western New York, Wisconsin, and in Nova Scotia. The ore is concretionary or oölitic in character and apparently a contemporaneous deposit enclosed within the shales or limestones. It is often highly fossiliferous, hence the name "fossil ore."

FIG. 54. An anticlinal fold in Silurian strata in the Appalachian Mountains. The conspicuous beds are sandstone. Near Clifton Forge, Virginia. (Photo by J. S. Grasty.)

Directly above the Clinton beds lie the *Niagaran* dolomitic limestones with a still wider distribution than the Clinton. Its type locality is at Niagara Falls, where it has been divided into the *Lockport* and *Guelph* dolomitic limestone formations. The resistant rock at the crest of Niagara Falls is Lockport dolomite. Middle Silurian time was another great limestone-making age almost comparable to that of the mid-Ordovician. In the United States, Niagaran limestone is known throughout much of the upper Mississippi Valley and Great Lakes region, southward to Tennessee, and westward to Missouri, Oklahoma, and northern Texas. In Canada it is widely distributed in Manitoba, just west of

Hudson Bay, and in the Arctic Islands. Niagaran limestone also quite certainly occurs in parts of the western United States, though definite correlations usually have not been made. Coral reefs are of common occurrence in the formation. It should not be understood, however, that limestone was universally forming during Niagara time, exceptions being for example, Niagaran shales in central New York and in Nova Scotia.

Cayugan Series. The *Salina* formation rests directly upon, but is much less extensive than, the Niagara formation, being found only through parts of Pennsylvania, New York, Ontario, Ohio, and Michigan. Lithologically the formation is quite variable, including all the common types of sediments as well as waterlime (hydraulic limestone), red shales, and salt and gypsum beds.

In New York salina salt beds underlie most of the western part of the state or an area of about 10,000 square miles. Sometimes there is one bed and sometimes several interstratified with other rocks. Single beds locally attain a thickness of from 50 to 80 feet. In the southern part of the state the salt is most deeply buried under later rocks, a well at Ithaca having passed through 248 feet of salt in seven beds below 2244 feet from the surface. Toward the north the beds gradually come near the surface. Important salt beds also occur near Cleveland, Ohio, and Detroit, Michigan. The salt beds are in the lower part of the Salina formation. In western New York there are extensive beds of gypsum in the upper Salina.

Overlying the Salina beds, but considerably more extensive, are the limestones and waterlimes of *Cobleskill, Rondout,* and *Manlius* ages which reach from Pennsylvania and New York westward to Indiana and Wisconsin.

Silurian Strata in the West. Definite subdivisions and correlations of the Silurian strata in western North America have seldom been made, but in certain regions, like parts of the Basin and Range Province, there are great successions of strata (largely limestones) ranging in age from Late Ordovician to Permian, including some Silurian in widely scattered small areas.

Igneous Rocks. Plutonic rocks of Silurian age are practically unknown in North America, but volcanic rocks—both lavas and tuffs—occur in great abundance in parts of Maine, New Brunswick, and Nova Scotia. Silurian volcanics also occur in southeastern Alaska.

Structure of Silurian Rocks. As in the case of the Ordovician, so the Silurian system in New England, the Appalachian Mountains, the mountains of Oklahoma, and the mountains of the west is usually more or less highly folded and faulted. Elsewhere, as throughout the great Interior Lowland, they are but little disturbed from their original horizontal position. In some places, as in parts of New England, the Silurian strata are more or less metamorphosed.

Thickness of the Silurian System. From central to western New York the thickness of the Silurian system is from 2000 to 3000 feet. Its usual thickness is from 2000 to 6000 feet in the Appalachians, while in the Mississippi Valley the thickness is generally less than 1000 feet. The Niagaran limestone is a notable exception to the usually greater thickness of the early Paleozoic strata in the Appalachian region, since in Wisconsin it is some 700 to 800 feet thick, while in the east it is only from 100 to 300 feet. In Maine the Silurian system contains 6000 feet of strata and thousands of feet of volcanic rocks. A thickness of about 1000 feet of Silurian occurs in central Utah, and 2500 feet in Alaska.

Physical History

Early Silurian. We have learned that, as a result of physical disturbance toward the close of the Ordovician, much of the interior Paleozoic sea was drained, causing the land area to be so much enlarged that it was as extensive as at any time since the beginning of the Paleozoic era. This was essentially the geographic condition of the continent at the beginning of the Silurian. The boldest topographic feature was the presence of the newly formed Taconic Range along the Atlantic seaboard.

During Early Silurian (Medinan) time there was a more or less gradual encroachment of the sea until in the later Early Silurian time when about one-third of the continent was flooded. Most of the eastern one-half of the continent, excepting Appalachia, Antillia, and eastern Canadia, was covered by a shallow sea extending from the Gulf of Mexico to the Arctic Ocean, with an arm through the St. Lawrence Valley region to the North Atlantic Ocean. The coarse Medinan sediments, derived from the young Taconic Mountains and rejuvenated Appalachia, were laid down in this sea from New York to Alabama, while finer sediments and limestones were deposited farther west.

The Early Silurian seas of western North America were far more restricted, but their extent is at present rather imperfectly known. An

arm of the Pacific Ocean probably extended across southern California and Nevada into southern Idaho.

At the close of Early Silurian time the seas largely withdrew from the continent.

Middle Silurian.—In Middle Silurian time the sea first withdrew from Canada with the exception of the St. Lawrence region and part

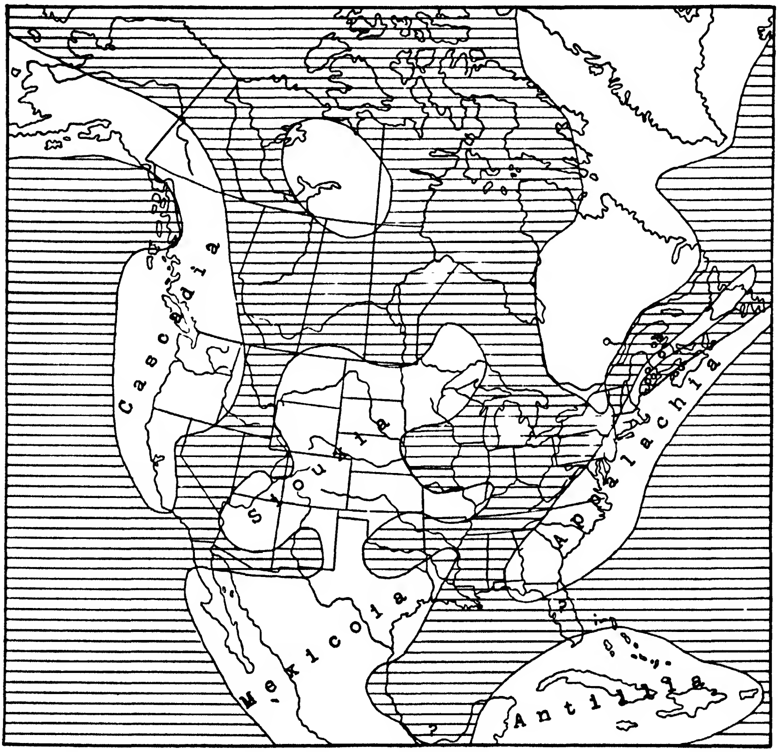


FIG. 55. Generalized paleogeographic map showing sea and land areas in North America during Middle Silurian time. This was the greatest Silurian sea. White areas, land; ruled areas, sea. Small circles show volcanoes in Maine, New Brunswick, and Nova Scotia. Principal data (modified) from maps by C. Schuchert and R. Chamberlin.

of the Arctic Islands. Then a grand marine invasion set in, especially over much of Canada, reaching a climax in late Middle Silurian (Niagaran) time. This was one of the four or five most extensive floods in the known history of North America. The general relations of land

and water, about as shown on map Fig. 55, were much like those of Late Ordovician time with the exception of the much larger Silurian land area (Siouxia) in the interior of the continent. More than one-half of North America was covered. That this vast Niagaran sea was a shallow-water (epeiric) sea is definitely known for reasons similar to those given in the discussion of the broad Ordovician seas.

There was much Silurian volcanic activity, particularly in the Middle Silurian, in eastern Maine, New Brunswick, and Nova Scotia. Both lava-flows and fragmental materials piled up to thicknesses of thousands of feet over wide areas. Marine strata of Silurian age are often interbedded with the volcanics, thus proving that the latter were laid down under the sea. Volcanoes were also active in southeastern Alaska.

Middle Silurian time closed with extensive, but by no means complete, withdrawal of the sea from the continent.

Late Silurian. That a very appreciable retrogression of the Niagaran sea ushered in Salina time is proved by both the comparatively restricted distribution and the character of the Salina strata. Thus, in the eastern United States and Canada, Salina strata occur only through parts of Pennsylvania and southward to Virginia in the Appalachians, parts of New York, southeastern Ontario, Ohio, and Michigan, and they are quite generally characterized by red shales and sandstones, and by salt and gypsum deposits. Such materials imply arid climate conditions, with deposition in extensive lagoons or more or less cut-off arms of the sea, rather than typical open sea conditions. At the same time arms of the sea existed in the St. Lawrence Basin, and probably across southern California and Nevada.

Since the immediately overlying Cayugan formations (Cobleskill, Rondout, and Manlius) are mostly marine deposits and more extensive than the Salina, it is evident that there was at least a partial restoration of more widespread marine waters in the eastern United States during later Cayugan time. This later Cayugan sea spread from eastern New York westward over the Salina lagoon areas and into eastern Wisconsin, and from eastern New York southward through the Appalachian district. The St. Lawrence and California-Nevada arms of the sea still persisted. As far as known the rest of the continent was dry land.

In addition to these broader and more important geographic changes during the Silurian period, there were of course various minor and generally local changes of relative level between land and sea, some of these now being known and some not yet determined.

Close of the Silurian.—At the close of the Silurian, or opening of the Devonian, the Cayugan sea withdrew from the area from central New York to Wisconsin, and but few comparatively small parts of North America remained submerged, such as the area extending from central New York through the northern Appalachian region.

There appear to have been no mountain-making (orogenic) movements, and no important epeirogenic disturbances at the close of the Silurian in North America. Because of the comparatively quiet and gradual transition into the succeeding period, the Silurian and Devonian systems are usually not sharply separated from each other, and often, as in New York and in the Appalachian region, there has been difficulty in satisfactorily dividing the systems. In the Interior Lowland region, however, the two systems are usually separated by a rather important disconformity because either Late Silurian or Early Devonian strata (or both) were never deposited over most of that region.

Climate

The general distribution and character of the rocks and their fossil content point to more uniform climatic conditions than those of today. Fossils in the Arctic Silurian rocks are not essentially different from those of low latitudes.

From central New York across to Michigan at least, there was an arid climate during the Salina epoch, as already mentioned, but this was probably only local.

Economic Products

Silurian sandstones and limestones are extensively quarried for building purposes, or the limestones burned to make quick-lime. The water-limes of late Silurian age were until quite recently considerably used for the manufacture of hydraulic cement, especially in the Hudson Valley of New York state.

Mention has been made of the widespread occurrence of hematite iron ore in the Clinton formation. This ore is mined to some extent in central and western New York, but in the Birmingham, Alabama, district, which is the second greatest iron mining region of America, the Clinton formation is the source of the ore.

Another important economic product of Silurian age is the salt of the Salina formation, already described. Many millions of barrels of salt are obtained yearly from these salt beds, especially in New York and Michigan. The usual method of procuring the salt is to pump

brine from deep wells which have been drilled into the salt beds, the brine then being evaporated to dryness.

Much gypsum is mined along the lines of outcrop of Cayugan strata in western New York.

Oil and gas are obtained from the Clinton sandstone of Ohio, some gas from the Medina sandstone of New York, and some oil from Silurian limestone in Kentucky.

Foreign Silurian

The Ordovician division of Europe into two great provinces or basins of deposition—northern and southern—was continued in the Silurian, though the latter strata are not so widely distributed. The fossils of these two provinces show greater differences than does the northern province as compared with North America, or even other continents. This implies a lack of free communication between the southern European province and the more typical Silurian provinces of the earth.

As in America, European Silurian strata are largely concealed beneath later formations. Usually the Silurian rests conformably upon the Ordovician, except in the British Isles. Also in most of Europe the transition to the Devonian was gradual, except in the British Isles, where the Silurian strata were tilted and eroded before the deposition of the Devonian. In much of the southern province the rocks are folded and tilted, though this deformation took place sometime after the close of the Silurian. In mid-Silurian, as in North America, much limestone was formed across the British Isles, southern Scandinavia, and well into Russia. Silurian strata of Europe are not as thick as those of the two immediately preceding systems, being from 3000 to 5000 feet in the British Isles, and generally less elsewhere.

In Europe the Silurian period closed with mountain-making on a grand scale. Across the northern British Isles and through the whole length of Norway, Silurian and older strata were highly folded, profoundly thrust faulted, and intruded with large granite batholiths. This has been called the *Caledonian Revolution*. Only the roots of the original Caledonian Mountains now remain. Considerable mountain-making also took place through northern France, southern Germany, and into Austria.

In other continents Silurian rocks have seldom been well studied and separated from the Ordovician, though they are definitely known in Siberia, China, Burma, the Himalayas, Turkestan, northern Africa, Australia, New Zealand, and Brazil.

CHAPTER XII

EARLIER PALEOZOIC LIFE

(Age of Invertebrates)

General Considerations

Abundance of Marine Life. Hundreds of species of fossils (largely of invertebrate animals) have been unearthed from Cambrian strata, and, as far as now known, they all represent marine forms. Furthermore the widespread Ordovician and Silurian seas literally swarmed with marine organisms, few rock systems containing a fuller record of marine forms than the Ordovician because of very favorable conditions of fossilization. Schuchert states that over 1600 species of animals are known from the Middle Ordovician alone. The Silurian record is nearly as great.

Scarcity of Land Organisms and Vertebrates. Thus far no fossil land animals have been found in either Cambrian or Ordovician strata, but some occur in the Silurian. Very primitive, low-order, land plants seem to be represented only by spores in Cambrian strata, and by recognizable plant forms in the Ordovician and Silurian. The scarcity of such fossil forms may be because the widely prevalent oceanic conditions were unfavorable for their fossilization, but it is also likely that land organisms had not progressed far or become very abundant so early in the history of the earth.

Vertebrates are unknown from the Cambrian, and if any existed then we know, from the record of vertebrates of succeeding periods, that they must have been of the very simplest types. Ordovician and Silurian rocks have yielded a scant record of vertebrates. These statements are of special significance in regard to the evolution of life on the earth because, as far as known, all land-dwelling organisms, and all vertebrates, have developed (evolved) since Cambrian time.

Stage of Evolution of Cambrian Life. The life of the Cambrian possesses a particular importance because, excepting the few scant or-

ganic remains found in upper Proterozoic rocks, the rocks of this age contain the oldest known great assemblage of distinct fossils. Even here, however, the organic record is very incomplete both because many Cambrian fossils have not yet been discovered and because a vast number of Cambrian organisms must never have been preserved as fossils. Although Cambrian fossils are scant as compared with those of other Paleozoic systems, nevertheless a striking fact is the large number and complexity of organisms represented. All the phyla or sub-kingdoms of invertebrate animals are represented, though nearly always by only the simpler types of each sub-kingdom, and this together with the positive evidences for pre-Cambrian life, makes it perfectly evident that organisms existed and developed (evolved) for a vast length of time before the opening of the Cambrian. It is generally agreed that fully half of the evolution of animals had taken place before the beginning of the Cambrian period, but that plants had not developed beyond the single-celled stage.

In spite of so much pre-Cambrian evolution of animals, it is to be remembered that, as a result of post-Cambrian evolution, literally enormous advancement has been made, so that Cambrian forms are really simple or primitive as compared with many of the highest living forms. To illustrate, there is a vast gulf between the degree of organization of the highest mammals of today and the highest forms (simple arthropods) of Cambrian time, and all of this development has been gradually accomplished since Cambrian time.

Passing upward even within the Cambrian system, the animal fossils show a gradual progress toward more highly developed or organized forms.

Apparent Suddenness of Appearance of the Cambrian Forms. The apparent suddenness of appearance of so many highly developed organisms even in the early Cambrian has caused much discussion by way of attempted explanation. Geologists are agreed that this seeming sudden appearance of so many forms is due to imperfection of the older record either because of unfavorable conditions for the preservation of fossils in the pre-Cambrian sediments, or because fossils, though once present in those rocks, have been obliterated by subsequent changes or metamorphism. Further, it is agreed that the first organisms were plants because animal life is ultimately dependent upon vegetable matter as a food supply.

It should be recognized that the metamorphic, or crystalline, character of all Archean and many Proterozoic rocks is obviously unfavorable for preservation of determinable fossils. Thus, Archean sedimentary rocks have flakes of graphite (carbon) disseminated through them and, though such carbon is of organic origin, the original organic structures have been entirely obliterated so that crystallized carbon only remains after the intense metamorphism. Such an explanation, however, does not by any means answer the whole question, because, at a number of localities, thousands of feet of non-metamorphosed pre-Cambrian strata are known and, except in very few cases in the later of these rocks, distinct fossil forms of animals are not known.

Brooks has advanced the hypothesis that the early living forms (plants and animals) were single celled, and that they originated and lived in the surface portions of the ocean. Because of the lack of severe struggle for existence in such environment, pelagic (free-swimming) plants have to this day remained largely primitive or single celled. For similar reasons the unicellular animals long failed to evolve higher forms because of easy existence in contact with much food and sunlight. Such forms were of gelatinous consistence and not favorable for preservation as fossils. Not until the attachment to the bottom or along shore were conditions favorable for the development of higher forms by the aggregation of cells. The plants first spread to the shore waters and thence over the land, so that gradually the shore waters became clearer and richer in organic material and hence more suitable habitats for animals. The animals once established along shore, about the beginning of the Cambrian or late in the pre-Cambrian, are conceived to have made rapid progress in evolution because the struggle for existence became severe on account of greater crowding in this more restricted environment. Support became necessary as well as means of defense, therefore hard parts were developed, and such hard parts could be preserved as fossils. In harmony with this hypothesis is the important fact that pre-Cambrian and early Cambrian fossil shells are mostly very thin, heavy shells apparently not having been evolved till later.

Another hypothesis "assumes that the first forms of life were simple plants that originated in the land waters. .... This hypothesis further assumes that the early animals, to a greater or less degree, had their origin in the same waters, and like the plants on which they were dependent spread thence to the sea and out upon the land. It is assumed that there might be considerable development of aquatic forms of animal life . . . in the land waters before they became denizens of the seas,

and their appearance in the latter might be at some rather advanced stage of their evolution and hence be seemingly sudden." [1]

PLANTS [2]

In order to gain even an elementary knowledge of the history and evolution of plants, the reader should bear in mind the important fact that plants of higher, more complex types came into existence during

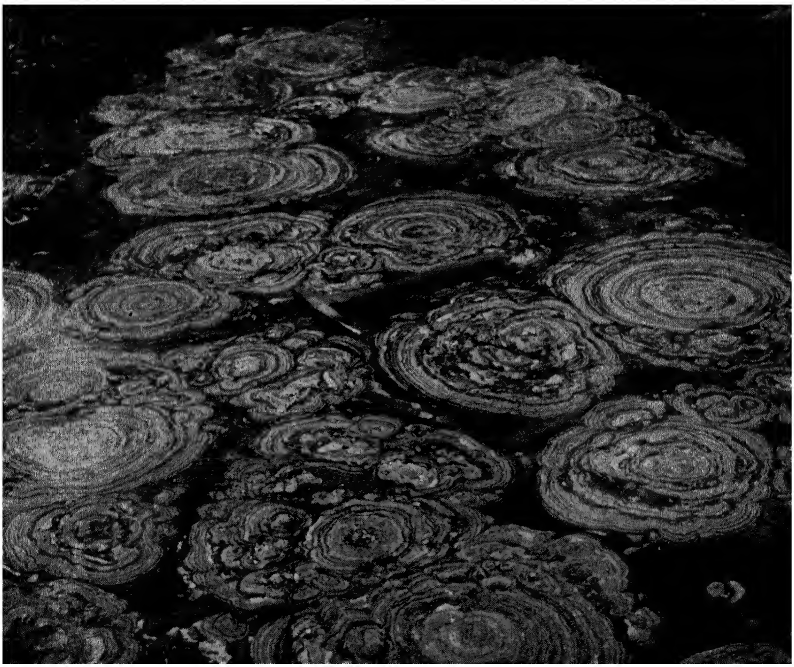


FIG. 56. Calcareous algae, *Cryptozoön proliferum,* forming a reef in Upper Cambrian limestone near Saratoga Springs, New York. (After H. P. Cushing, *N. Y. State Mus. Bul. 169.*)

geological time in almost exactly their general botanical order of classification (Appendix A). In other words, from the primitive, single-celled plants of Archeozoic and Proterozoic times, there have evolved more complex forms culminating in the highly organized plants of today.

[1] Chamberlin and Salisbury: *Geology,* Vol. 2, p. 302.

[2] In the study of the history of life from the Cambrian to the present in this book the student should refer to the outline classifications of plants and animals in Appendix A.

There are certain rather obscure impressions and cluster-like forms in Cambrian rocks which may be seaweeds, but their identification is often unsatisfactory. In the earlier Paleozoic periods simple plants at least must have been abundant since animals ultimately depend upon plants for food. Their scarcity as fossils is doubtless due to the unfavorable nature of the simple (soft) marine plants for fossilization.

Recently certain problematical Cambrian fossils, long known by the name "Cryptozoön," have been determined as algae by Walcott. They secreted concentric layers of carbonate of lime and lived in water. In some localities, as near Saratoga Springs, New York, distinct beds or "reefs" of such algæ occur in limestone (Fig. 56).

There is no evidence that any types of plants other than single-celled water-dwelling forms existed before Cambrian time. Recently (1937) the discovery of what are probably minute spores of very primitive land plants in Cambrian strata has been reported. If true, this is the oldest known record of land-plant life.

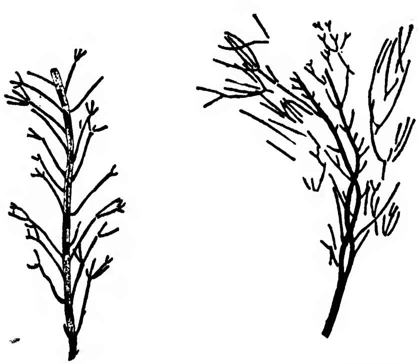


FIG. 57. Ordovician seaweeds, *Callithamnopsis fructicosa.* (After Ruedemann.)

Various kinds of seaweeds (marine algae) are definitely known from Ordovician limestones and shales (Fig. 57), and also from Silurian sandstones.

Definite knowledge of Ordovician land plants is very scant, making the following recent (1935) discovery especially significant. According to Science Service "fossils of fernlike plants of very simple structure, with a great deal of branching stem, but with nothing that can be surely identified as leaves, have been found in a deposit of Lower Ordovician limestone in Wyoming by E. Dorf. Together with similar fossils found in a very few scattered places over the earth, they belong to the oldest known groups of land plants known as Psilophytales."

Our knowledge of Silurian land plants is also very meager. Some mosslike and fernlike forms of doubtful affinities have been reported. In regard to certain fragments of plants found in Silurian strata in England, Sweden, and Australia, Seward says that "they afford evidence of the existence of two Silurian types, probably terrestrial, which agree closely with forms characteristic of the earlier Devonian floras, and of a

third type that appears to be peculiar to this meager pre-Devonian flora."

Considering the profuse land vegetation of the next (Devonian) period, it seems certain that their progenitors must have been well represented in the Silurian, and that either more of their remains will be discovered, or that the conditions for their preservation were unfavorable.

Animals

Some knowledge of the classification and main characteristics of the more important groups of animals is a fundamental consideration in the study of the life of the past ages of geologic time, particularly in its bearing upon the great doctrine of organic evolution. In Appendix A a simple classification includes various important subdivisions of animals, most of which are often represented in fossil form. Reading downward in this table, there is a gradually increasing complexity of structure, ranging from single-celled forms to the most highly organized animals which ever lived. Just as it is true of the history and evolution of plants, so here it is a remarkable fact that animals have evolved, or become more and more complex, as geologic time has gone on.

Protozoans. These single-celled animals have left a fossil record ranging through earlier Paleozoic time. Perhaps the best known of these tiny creatures were the foraminifers which secreted shells of lime carbonate (Fig. 360). Such creatures now swarm in large areas of surface sea waters. Radiolarians, which had shells of silica, also existed through earlier Paleozoic time. Many other kinds of protozoans doubtless existed, but very few secreted shells, and hence not many species were favorable for fossilization.

The early Paleozoic protozoans were very much like the modern marine forms, and it is an interesting and important fact that such very simple types have persisted throughout all of geologic time from the Cambrian to the present, while profound evolutionary changes were taking place in the animal kingdom.

Porifers. Sponges represent the simplest of the many celled animals. They are porous saclike forms (Fig. 58). They ranged through the first three Paleozoic periods, and to the present day, with no outstanding evolutionary change. Usually only those sponges which secreted skeletons are found as fossils. In the Silurian strata of western Tennessee sponges are very abundant.

Cœlenterates. *Hydrozoans* were represented by both the so-called "jellyfishes" and the graptolites. Recognizable casts and impressions

FIG. 58. A Cambrian sponge, Leptomitus zitteli. (After Walcott.)

FIG. 59. A Cambrian sponge or coral, *Archeocyathus rensselaericus.* (After Walcott.)

of jellyfishes (Fig. 60), which creatures consist wholly of soft parts, occur in Cambrian rocks and these are remarkable freaks of fossil preservation.

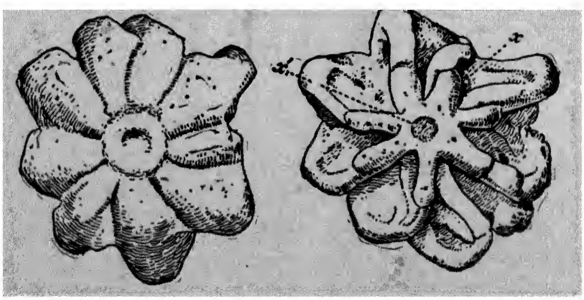


FIG. 60. A Cambrian jellyfish, *Brooksella alternata. A,* top; *B,* bottom. (After Walcott, from Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company.)

Graptolites (Fig. 61) were common in Cambrian, Ordovician, and Silurian times. They were slender, plumelike, delicate forms consisting of colonies of cells. They were pelagic or free to float in the open sea.

One genus of graptolites, confined to a horizon near the summit of the Cambrian, is almost world-wide in its distribution and beautifully illustrates the importance of such forms for purposes of correlation over wide areas. The Ordovician may be said to have been the period of culmination of this remarkable, long extinct group of animals. They are so abundant and varied in Upper Ordovician shales that definite stages or horizons have been determined largely by their use. Since the graptolites were mostly floating forms and widely distributed at a given time, they have been of great value in correlating even minor subdivisions of the system in such far separated regions as Great Britain, eastern North

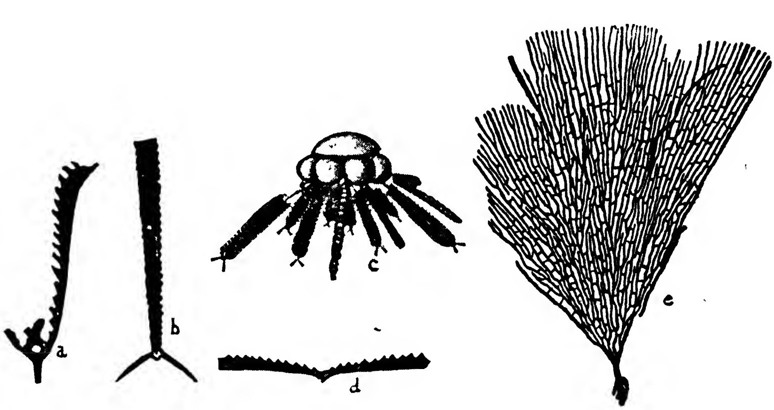


FIG. 61. Ordovician graptolites: *a, Tetragraptus fructicosus; b, Climacograptus bicornis; c, Diplograptus pristis; d, Didymograptus nilidus; e, Dictyonema flabelliforme.* (*a, b, d,* after Hall; *c,* after Ruedemann; *e,* after Matthew.)

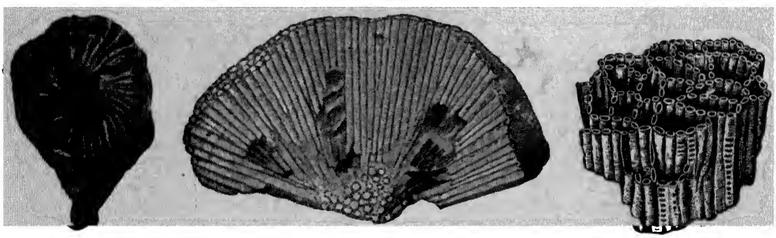
America, and Australia. When it is further stated that all known graptolites are largely confined to the first three great fossiliferous systems (Cambrian, Ordovician, Silurian), with rare occurrences in the Devonian and Mississipian, their additional importance as stratigraphic indices becomes evident. In Fig. 61 the forms represent skeletons or axes of colonies, a single or a double row of protoplasmic cells having been arranged along an axis. Forms with cells on both sides of the axis were very characteristic of the Ordovician.

In Silurian time the more complex colonies, such as branching forms and those with double rows of cells on their axes, were nearly extinct, the simple forms mostly only remaining.

Anthozoans (corals) were rather doubtfully present in the Cambrian because the fossil forms so greatly resemble sponges (Fig. 59), but re-

cent study seems to indicate that some at least were true corals. Locally such coral-like forms were common enough to form reefs. It seems quite clear that the corals evolved from Cambrian sponges.

Ordovician corals were common, more especially where the mid-Ordovician limestones were forming. It will serve our purpose to divide the principal Paleozoic corals into three groups or types as follows: (1) *Cup corals* (solitary or compound), (Fig. 62a); (2) *honeycomb corals* (compound), (Fig. 62b); and (3) *chain corals* (compound), (Fig. 62c). These Paleozoic corals were all Tetracoralla, that is, the radiating partitions (septa) of the individuals or polyps were four in number or multiples of four, while modern corals, which first appeared in the Permian period, are Hexacoralla or Octacoralla. Modern corals are nearly all profusely branched and the polyps are very small, while



a *b* *c*

FIG. 62. Silurian and Devonian corals: *a*, Cup coral, *Zaphrentis roemeri* (M. Edwards and Haime) (Devonian form); *b*, Honeycomb coral, *Heliolites pyriformis* (Guettard); *c*, Chain coral, *Halysites catenulatus* (Linn.).

Paleozoic corals were rarely branched and the polyps were much larger, the cup corals usually ranging from half an inch to a foot or more in length. All three types of corals above mentioned existed in the Ordovician, but solitary cup corals were predominant. Compound forms, especially honeycomb corals, were sometimes locally abundant. Among modern corals the compound or colonizing forms are by far more common than the solitary forms.

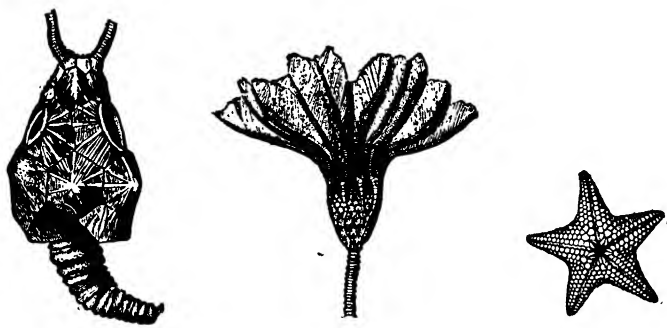
Corals increased in prominence in Silurian time, and the simple *cup corals* of the Ordovician were superseded in importance by the colonizing or compound forms. *Chain corals*, which were rare in the Ordovician, reached their climax of development, but became nearly extinct by the close of the period. *Honeycomb corals* were also common.

Echinoderms. These are often called the "starfish" family. They are marine forms with a distinct body cavity, a very simple digestive

canal, a low-order nervous system, and a water circulatory system. They are nearly always radially segmented.

Of the stalked echinoderms the very simplest forms, called *cystoids,* are known from the Cambrian. There were the bladder-like forms, sometimes with rudimentary arms, set on segmented stems (Fig. 64a). *Holothuroids* ("sea cucumbers") have been found in the Cambrian of British Columbia. These are of special interest because they represent highly organized forms of echinoderms.

In the Ordovician all classes of the echinoderms were represented. Cystoids then reached their climax of development. *Blastoids* were rare and represented by very primitive forms with distinct cystoid affinities. *Crinoids,* often called "stone lilies" appeared and became prominent in



a b c

FIG. 63. Ordovician echinoderms: *a,* cystoid, *Pleurocystis filitextus; b,* crinoid, *Glyptocrinus dyeri; c,* asterozoan, *Paleasterina stellata.* (*a, c,* after Billings; *b,* after Meek.)

the Ordovician. They are (and were) animals with a complex, highly segmented, headlike portion attached to the sea bottom by a long segmented stalk (Fig. 64). The segments consist of carbonate of lime. Because of their hard parts they were well suited for fossilization, but after decay of the soft parts, the segments usually fell apart so that entire specimens are not common. *Asterozoans* (starfishes, Fig. 63c) and *echinoids* (sea urchins) were uncommon in the Ordovician, the latter having been represented by very primitive forms.

In Silurian time crinoids increased notably in numbers and species, as well as in complexity of structure (Fig. 64c). Hundreds of species are known. On some parts of the sea bottom they must have existed like miniature forests. Silurian asterozoans and echinoids were common.

Modern sea urchins have exactly twenty rows of calcareous plates tightly fitted together, while Paleozoic forms had a variable number of plates, and in some forms the plates were only loosely joined together, this latter feature apparently being a primitive characteristic.

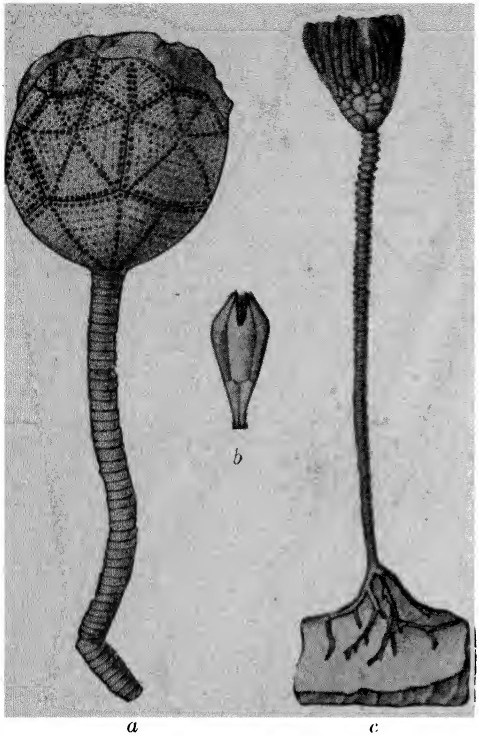


FIG. 64. Silurian echinoderms: *a*, cystoid, *Caryocrinus ornatus; b*, blastoid, *Troostocrinus reinwardti; c*, crinoid, *Eucalyptocrinus crassus.* (After Say, Troost, and Hall respectively.)

Worms. These are known to have existed since late pre-Cambrian time (Fig. 69). Tracks, borings, and impressions constitute most of their fossil record. Worms are of particular interest in the history of animal life because the arthropods and certain other invertebrate sub-kingdoms probably evolved from them.

Molluscoids. *Brachiopods,* next after the trilobites (simple crustaceans), are the most important Cambrian fossils (Fig. 65). There are two important general groups of brachiopods, namely, the inarticulates, in which the horny shells or valves are not joined together by a hinge, and the articulates, in which the heavier calcareous shells are joined together by a hinge structure. The former are simpler and lower in organization, and, from the standpoint of evolution, it is important to

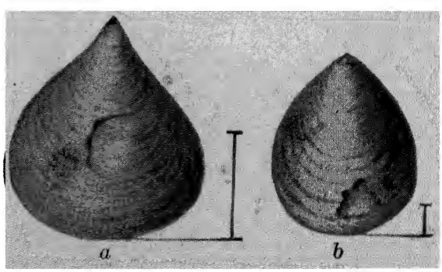


FIG. 65. Cambrian brachiopods: *a, Lingulella prima; b, Lingulella acuminata.* (After Walcott.)

note that Cambrian (and probably pre-Cambrian) brachiopods were mostly inarticulates, the articulates not becoming common till in the Upper Cambrian. In the post-Cambrian periods the articulates greatly

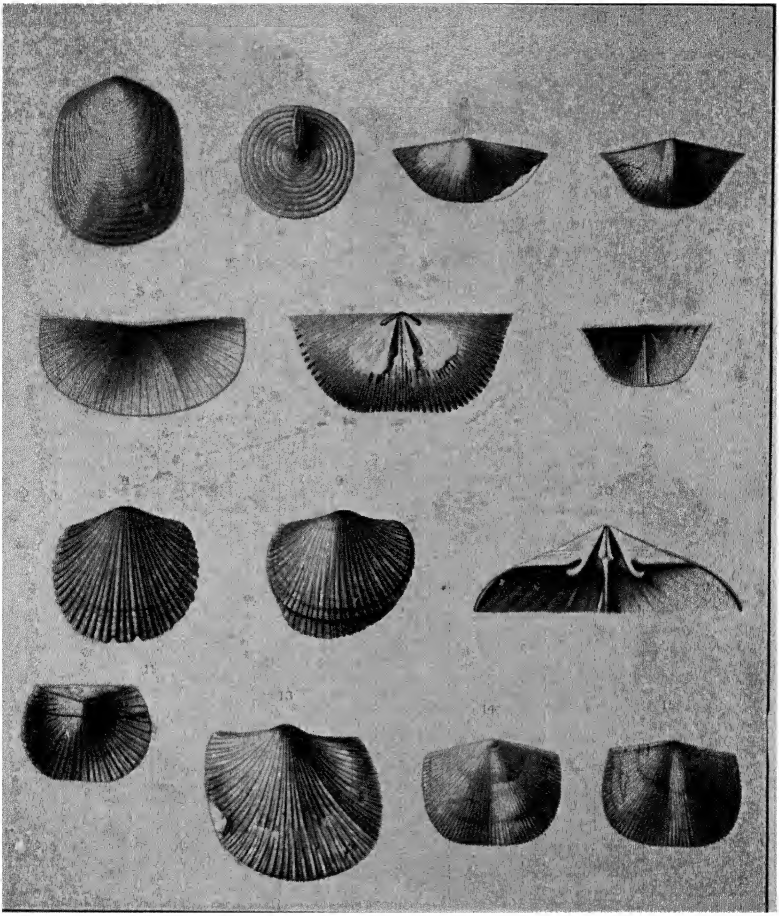


FIG. 66. Ordovician brachiopods: *1*, *Lingula rectilateralis*; *2*, *Orbiculoidea tenuistriata*; *3*, *4*, *5*, *6*, *Plectambonites sericeus*; *7*, *Plectambonites centricarinatus*; *8*, *Plectorthis whitfieldi*; *9*, *10*, *11*, *Plæsiomys retrorsa*; *13*, *Plæsiomys porcata*; *14*, *15*, *Clitambonites americanus*. (From Ruedemann, *N. Y. State Mus. Bul. 162*.)

outnumbered the inarticulates, and they are the most common of all fossil shells in the Paleozoic rocks. The brachiopods stand out conspicuously as a remarkably persistent class of animals ranging from pre-Cambrian

time to the present, and, although there have been very many species and genera changes, the class as such has been very little changed. A few genera, but no species, have persisted from the Cambrian to the present. At least 7000 species of brachiopods are known, most of them from the Paleozoic, but only about 200 species now exist. Many hundreds of species are known from the Paleozoic rocks alone, and by studying their gradual changes in species and genera, they have come to rank among

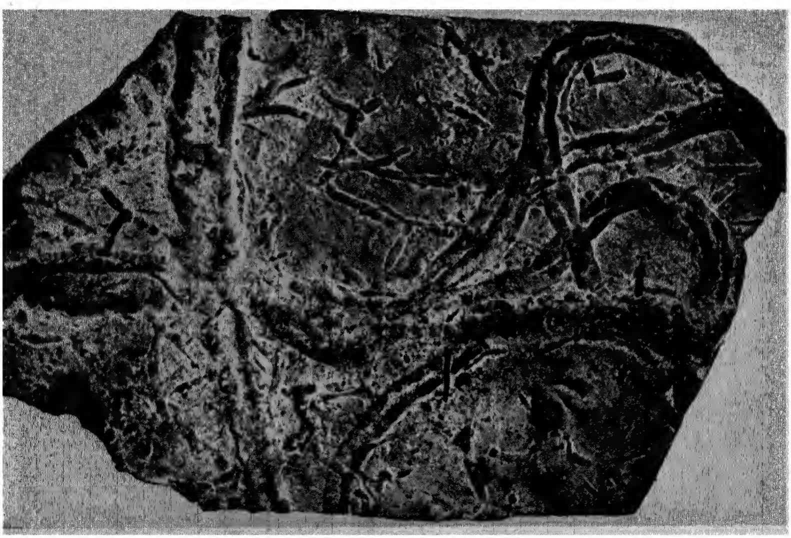


FIG. 67. Animal tracks on Silurian sandstone from Clinton, New York. Length of specimen, 10 inches.

the most valuable fossils as geologic time markers and for purposes of correlation.

Brachiopods became much more abundant, more varied, and more complex in Ordovician time (Fig. 66). Those with hinged shells (articulates) greatly outnumbered the inarticulates for the first time. Also the shells usually were thicker and more difficult for their enemies to open because of long-hinged lines, or a fluted or ribbed structure, or both. As for the early Paleozoic in general, nearly all were straight-hinged. Many genera and species are known, certain of them having been much used in subdividing the Ordovician system. Along with the trilobites, the brachiopods were the most prominent known organisms of the period. About 300 species are known from the Middle Ordovician of North America alone

In Silurian time brachiopods continued to be the most prominent of all organisms as regards both number of individuals and species, and this in spite of the fact that very few Ordovician species, and not many genera, continued from the Ordovician into the Silurian. Two genera, Spirifer and Pentamerus, made their first appearance and were especially prominent in the Silurian, but became even more so in the Devonian. The Spirifer developed a long, straight, hinge line, while the Pentamerus had a sort of hook-shaped beak projecting over the hinge line.

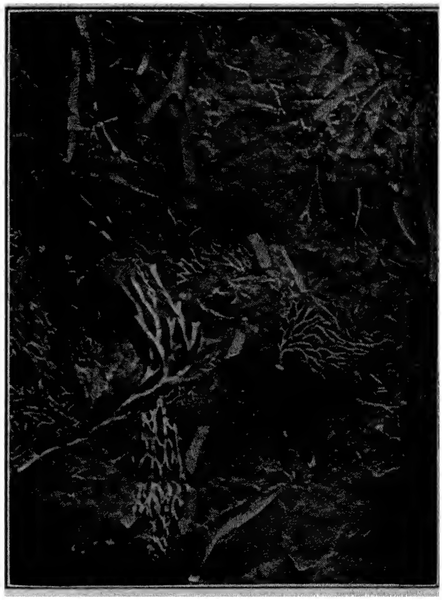


FIG. 68. Various Ordovician bryozoans on a slab of limestone. (After R. S. Bassler, U. S. National Museum.)

Among the molluscoids, the *bryozoans* (so-called "sea mosses") are first known from the Ordovician when they were abundant, often as reef builders, particularly in the later portion of the period. Hundreds of Ordovician species are known. Though structurally (organically) very closely related to the brachiopods, they are far different from them in outward appearance, while they look so much like the corals as often to be distinguished from them with difficulty (Fig. 68). The bryozoans afford a fine illustration of a class of creatures whose genera have changed very little from very ancient times to the present day. They continued to be common in the Silurian period.

Mollusks. These are still more highly organized than the molluscoids, having more or less well-developed heads and locomotive organs. They are very abundant and diversified today, and many thousands of species are known only in fossil form. The simplest of these are the *pelecypods* which, like the brachiopods, live between two shells working on a hinge, but unlike the brachiopods, these shells are not symmetrical with reference to a plane cutting them at right angles to the hinge line. The earliest known pelecypods are from the Ordovician (Fig. 70) after

which they developed greatly during Paleozoic time.

Paleozoic pelecypods, like their modern representatives (e.g. clams and oysters), appear to have thrived unusually well where muds and sands were being deposited, and they are therefore much more numerous as fossils in the Upper Ordovician shales and sandstones. One important contrast for the reader to keep in mind is the distribution of the pelecypod bivalves through geologic times as compared with the brachiopod bivalves. Brachiopods were very abundant and more varied than pelecypods in the earlier Paleozoic periods, but they have steadily declined almost to extinction at the present time, while pelecypods have steadily increased in numbers and variety to recent time.

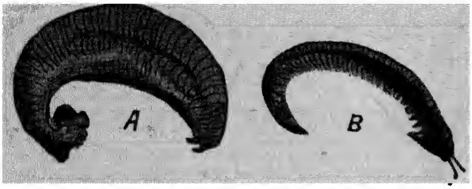


FIG. 69. Cambrian worms: A, Ottoia prolifica; B, Worthenella cambria. (After Walcott.)

Gastropods possess distinct heads, eyes, and tentacles. They inhabit one-chambered, more or less coiled shells. They have ranged from earliest Paleozoic time to the present (Fig. 71). A remarkable fact about them is that through all of those many millions of years they have persisted with no really conspicuous evolutionary change. From their meager beginning in the Cambrian they have, however, gone on increasing in variety of forms and number of individuals to the present, there now being fully 20,000 known species.

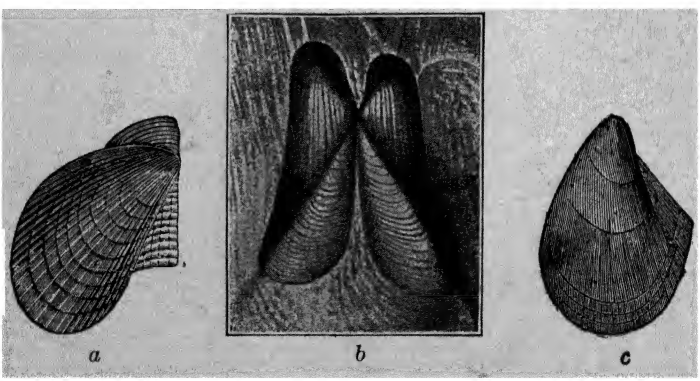


FIG. 70. Ordovician pelecypods: *a, Cardiola interrupta* (Hall); *b, Orthodesma? subcarinatum* (Ruedemann); *c, Ambonychia bellistriata* (Hall).

Cephalopods represent the highest mollusks with well-defined foot structures, heads armed with tentacles, and large complex eyes. The more primitive forms are the chambered cephalopods, so called because the external shell is divided into compartments which are successively

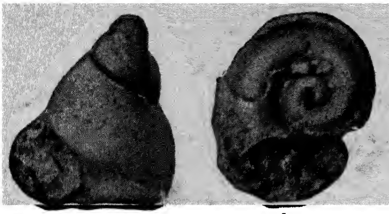


FIG. 71. Cambrian gastropods: *a, Matherella saratogensis; b, Pelagiella minutissima.* (After Walcott.)

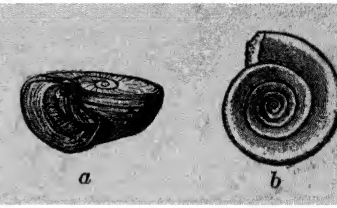


FIG. 72. Ordovician gastropods; *a, Maclurea logani* (Salter); *b, Ophileta complanata* (Vanuxem.)

built up and abandoned by the animal as it grows. The higher (non-chambered) types did not exist in the Paleozoic.

All known Cambrian forms were primitive types and not very common.

"The largest, most powerful, and perhaps the most predaceous of the known forms of Ordovician life were the cephalopods, which seem to

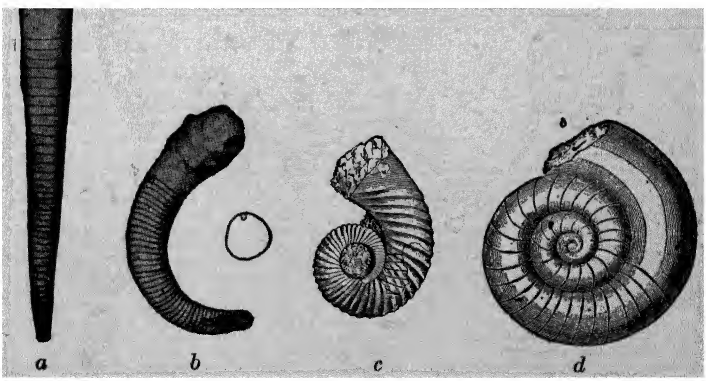


FIG. 73. Ordovician cephalopods: *a, Orthoceras sociale* (Hall); *b, Cyrtoceras neleus* (Hall); *c, Trochoceras-like* form (Silurian specimen after Barrande); *d, Trocholites ammonius* (Hall).

have developed into prominence with extraordinary suddenness. Unless the fishes, of which very little is known, contested their supremacy, they were doubtless the undisputed masters of the sea. Their relics first appear at the time of the transition from the Cambrian to the Ordovician,

but they were then so far advanced and so widely differentiated from allied forms as to render it probable that they had already lived a long time. . . . The size attained by the Ordovician cephalopods was probably never surpassed by representatives of the class. Some of the shells were 12 or 15 feet in length, and a foot (maximum) in diameter. From this great size they ranged down to or below the size of a pipe stem."[1] These cephalopods all belonged to the tetrabranch or chamber-shelled subdivision of the class (Fig. 73).

The tetrabranch cephalopods, for two reasons, constitute one of the most interesting and instructive illustrations of evolutionary changes, ranging from the early Paleozoic to the present time, first because we have such an abundant record in the rocks of all these periods, and second because the evolutionary changes have expressed themselves in the external or shell portions in a remarkable and easily recognizable manner. The only known Cambrian tetrabranchs were of the very simple, straight, or curved chamber-shelled types like the Orthoceras and Cyrtoceras. In the Ordovician the straight form, e.g. *Orthoceras* (Fig. 73a) was still dominant, but many advances were made giving rise to more curved forms (e.g. *Cyrtoceras,* Fig. 73b), open-coiled forms (e.g. *Trochoceras,* Fig. 73c), and close-coiled forms (e.g. *Trocholites,* Fig. 73d). All of these forms belonged to the nautiloid division of the tetrabranchs, that is, their septa or chamber partitions, where in contact with the walls of the shell, were straight or at least very simple. Close-coiled nautiloids of the Ordovician greatly resembled the modern pearly nautilus, which is one of the very few living representatives of the now almost extinct nautiloids (Fig. 371). The persistence of these simple close-coiled forms from the Ordovician to the present is noteworthy. Ammonoids, that is to say tetrabranchs with more complex septa junctions, appeared in the Devonian and became increasingly prominent

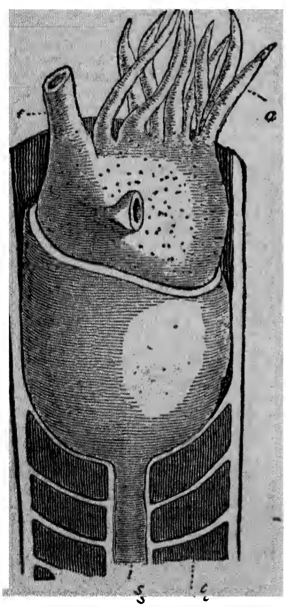


FIG. 74. An orthoceras restored. (After Nicholson, from Le Conte's "Geology," courtesy of D. Appleton and Company.)

[1] Chamberlin and Salisbury: *College Geology,* pp. 525-527.

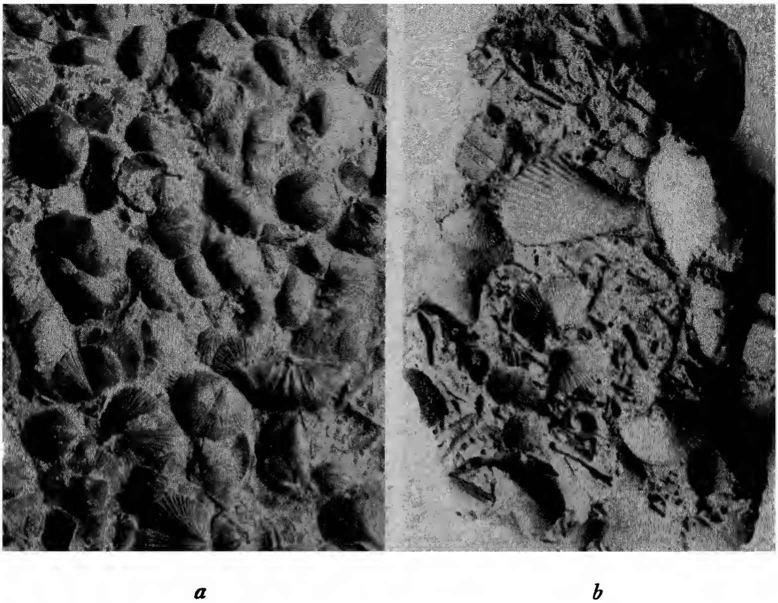


FIG. 75. Bits of Ordovician sea-bottom: *a*, brachiopod shells on limestone; *b*, crinoid, bryozoan, brachiopod, pelecypod, gastropod, and cephalopod remains in calcareous sandstone.

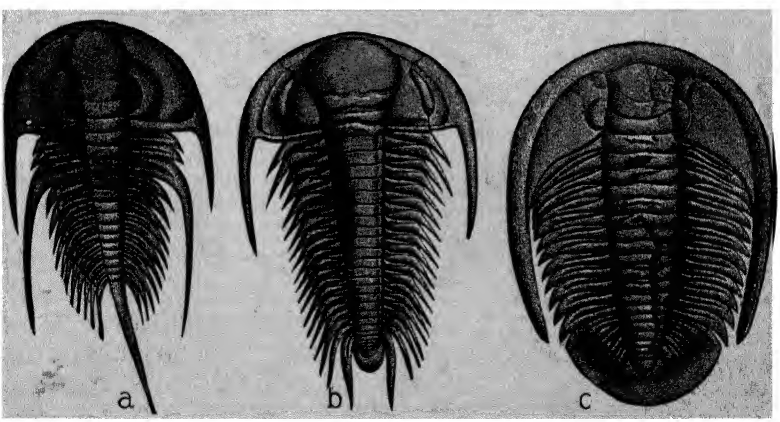


FIG. 76. Cambrian trilobites, restored forms: *a*, *Olenellus gilberti*, characteristic of the Lower Cambrian; *b*, *Paradoxides bohemicus*, characteristic of the Middle Cambrian; *c*, *Dikellocephalus pepinensis*, characteristic of the Upper Cambrian. (From Chamberlin and Salisbury's "Geology," permission of Henry Holt and Company.)

well into the Mesozoic era, but they have not continued to the present.

Arthropods. These comprise the highest sub-kingdom of all invertebrate animals. They are characterized by longitudinal body segmentation, jointed appendages, and usually a pair of nerve centers in each segment. The simplest forms are the *crustaceans* (e.g. lobsters) which breathe by means of gills or through the body, have well-developed feel-

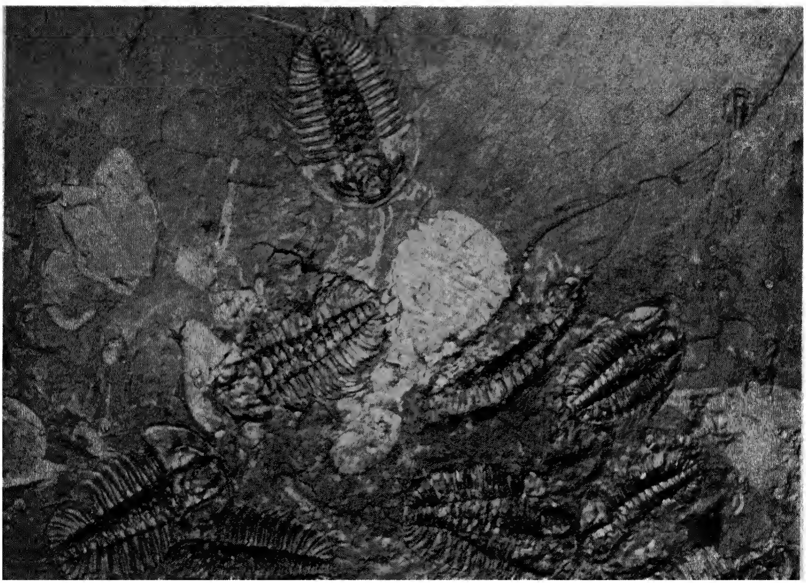


FIG. 77. Cambrian trilobites and other related fossils on a slab of shale from the southern Rocky Mountains of Canada. Much less than natural size. (After C. D. Walcott, courtesy of the Smithsonian Institution, Washington, D. C.)

ers, and a thin shell cover. The wholly extinct race of *trilobites,* classed among low-order crustaceans, were among the most common, interesting, and geologically important of Paleozoic animals (Figs. 76, 77). They are the simplest and most primitive of all arthropods, probably having evolved from a wormlike animal. They were progenitors of higher types of arthropods. We have seen that the threefold subdivision of the Cambrian system is based upon the changes in the trilobite fauna. Examples of the most characteristic Cambrian genera are shown in Fig. 76. They were inhabitants of the sea and they were among the most highly organized animals of the time. Trilobites persisted only till the close of the

Paleozoic era, and they were especially numerous in the earlier periods of that era. The name trilobite refers to the three-lobed character of the body. The creature possessed a distinct head-shield with compound eyes, and a more or less distinct tail-shield. Between the shields there was a highly segmented body portion. They ranged in length from an inch or less to about two feet. Nearly all of them crawled on the shallow sea bottom. "The trilobites display an extraordinary variety in form and size, in the proportion of the head-and-tail-shields, in the number of free segments, and in the development of spines. Already in the Cambrian this wealth of forms is notable, though far less than it became in the Ordovician. As compared with those of later times, the Cambrian trilobites are marked by the (usually) very small size of the tail-shield, the large number of free segments, and their inability to roll themselves up."[1]

Trilobites, which were the chief Ordovician arthropods, then reached their climax or culmination of development in numbers and species, more than a thousand species being known from this period alone (Fig. 78). These animals, after the brachiopods, appear to have been among the most numerous animals of the time. Their variation in size was much like that of the Cambrian, but their eyes were usually larger and better developed. Many Ordovician forms could roll themselves up, shrimp-like, in order to protect their soft under sides. With the rise of powerful enemies, first the giant cephalopods and then the fishes, the trilobites declined.

Silurian trilobites were perhaps more diversified than in any other period. "Like the decadent nations revealed to us in human history, they indulged in extravagant and futile eccentricities, ill befitting their approaching overthrow. Odd and highly ornate forms appeared in profusion (Fig. 79b, c), and in most instances the spines, tubercles, and horns which they produced seem to have had little or no real value in their life activities. We shall see in studying later periods that similar eccentricities mark the fall of other groups, such as the ammonites and the reptiles."[2]

Eucrustaceans of rather simple types were present in the Earlier Paleozoic, but they were not important. There were no real crabs or lobsters till much later.

Arachnids (e.g. *eurypterids*) are only sparingly known from the Cambrian. They were more common in the Ordovician. The *eurypterids,* greatly increased in numbers, species, and size, and they appear to have

[1] W. B. Scott: *An Introduction to Geology,* 2nd ed., p. 556.

[2] Blackwelder and Barrows: *Elements of Geology,* pp. 352-353.

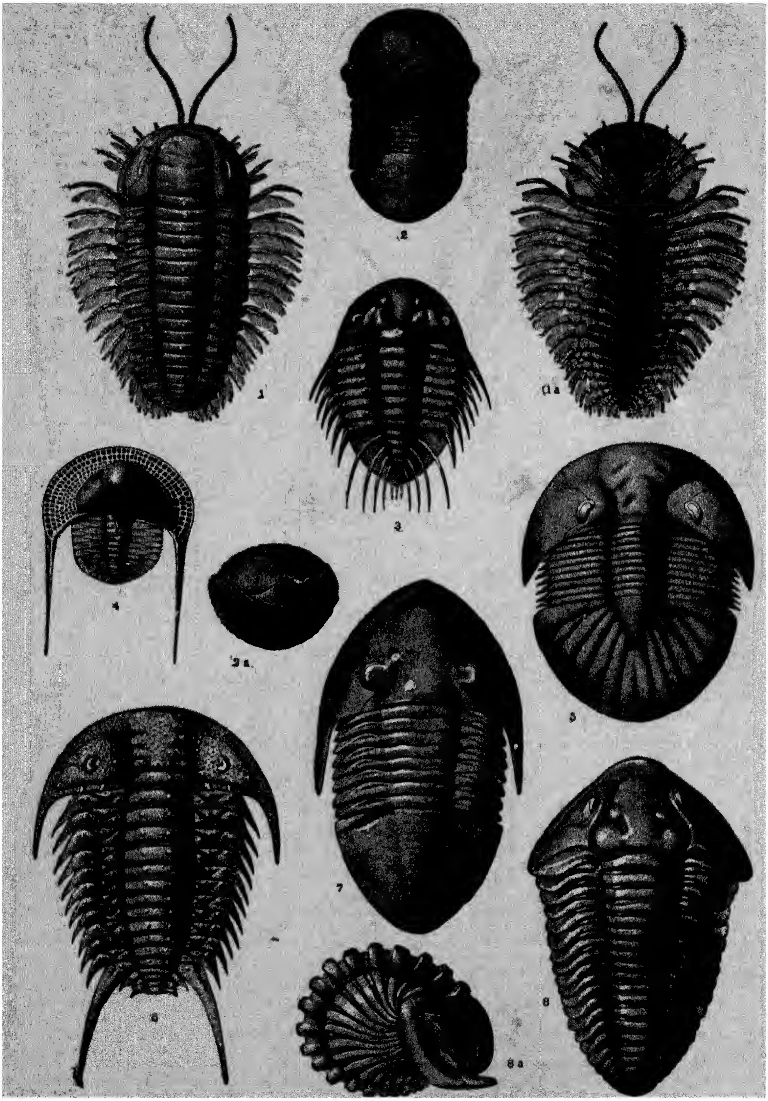


FIG. 78. Ordovician trilobites: *1, 1a, Triarthrus becki* (restorations by Beecher) *2, 2a, Bumastus trentonensis; 3, Acidaspis crosotus; 4, Trinucleus concentricus; 5, Bronteus lunatus; 6, Ceraurus pleurexanthmus; 7, Isotelus maximus; 8, 8a, Calymene callicephala.* (From Scott's "Introduction to Geology,' permission of the Macmillan Company.)

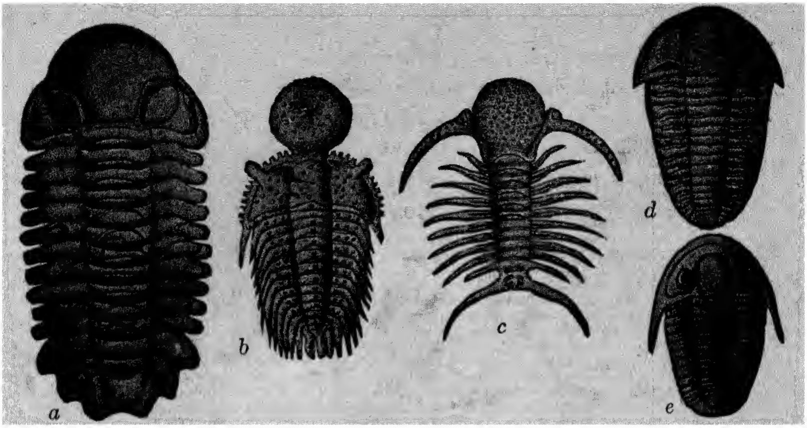


FIG. 79. Silurian trilobites: *a, Sphærexochus mirus* (Bey.); *b, Staurocephalus murchisoni* (Barr.); *c, Deiphon forbesi* (Barr.); *d, Calymene niagarensis* (Hall); *e, Cyphaspis christyi* (Hall). (From Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

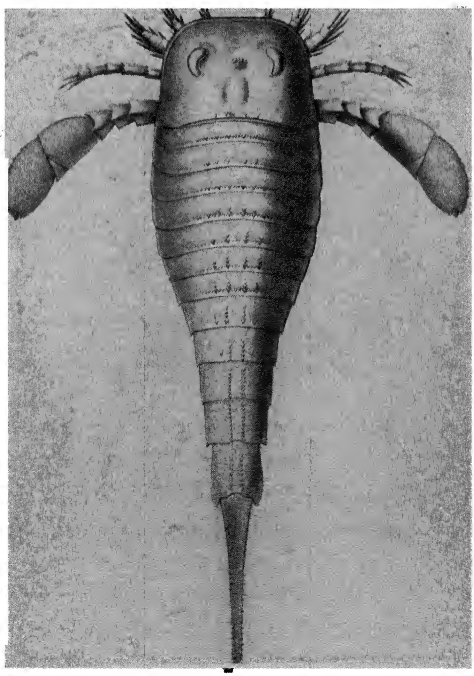


FIG. 80. A Silurian eurypterid, ***Eurypteris remipes,*** restored to show dorsal side. (After Clarke and Ruedemann, N. Y. State Mus. Mem. 14.)

culminated, in the Silurian. The following brief description, together with an examination of Fig. 80, will serve to give a fair idea of the appearance and structure of these remarkable creatures. In the typical eurypterid, a quadrate or semicircular head had behind it twelve movable segments making up the abdomen, and attached to the last segment was either a spine or plate-like tail. The five pairs of appendages all came out from the head portion, thus being markedly different from the trilobites. The first pair of appendages were much enlarged, sometimes pro-

FIG. 81. A Silurian scorpion, *Paleophonus caledonicus,* by Hunter after Peach. (From Le Conte's "Geology," permission of D. Appleton and Company.)

vided with pincers and sometimes not, while the fifth pair were usually long and they served as swimming paddles. They varied greatly in size, one species, from the Silurian, having attained a length of over six feet and so was one of the largest known arthropods. Many eurypterids appear to have been marine animals, while others probably lived in fresh or brackish water lagoons.

The arachnids included also the earliest known *scorpions* (Fig. 81). which were in many respects similar to the eurypterids. These scorpions

are to be classed among the very early, if not earliest, definitely known land or air-breathing animals to inhabit the earth.

Horseshoe crabs first appeared in the Silurian.

Vertebrates. From the standpoint of evolution, perhaps the most significant feature of the Ordovician is the occurrence of the earliest known vertebrates. These were very primitive fishlike forms such as *ostracoderms,* which have been found in Ordovician strata at certain places in Colorado and Wyoming. The fossils are mostly very fragmentary, consisting chiefly of scales or plates, but some nearly complete dermal plates are known.

The only known Silurian vertebrates were of very simple types, such as the *ostracoderms* and primitive *fishes,* probably *sharks.* All of the ostracoderms were small, odd-shaped creatures, but rather closely related to the more prolific Devonian forms to be described later.

When we consider the fact that fully one-half of known geological time had passed before the close of the Silurian, it is a remarkable fact, from the standpoint of evolution, that vertebrate life had made not more than a meagre beginning by Silurian time. This fact is even more impressive when we realize something of the tremendous advances made by the vertebrates and the great variety of their forms which have inhabited the earth since Silurian time, as outlined in the following pages of this book.

LATER PALEOZOIC TIME

CHAPTER XIII

ROCKS AND PHYSICAL HISTORY OF THE DEVONIAN

Origin of Name and Subdivisions

In 1839 Sedgwick and Murchison gave the name of Devonian to strata in the county of Devonshire in England where rocks of this age were first carefully studied.

In North America the New York subdivisions are taken as the standard, because the Devonian strata were first carefully studied there. The New York Devonian section is a remarkably complete one of very considerable thickness (minimum, 4000 feet), with not a single stage missing, except possibly the very lowest one, and with a surface distribution over fully one-third of the area of the state. There was practically continuous deposition of strata during Devonian time in New York, and if locally a stage or sub-stage is missing, it is present elsewhere in the state. It is doubtful if a greater degree of refinement of knowledge exists regarding so complete a section of the Devonian or of any other Paleozoic system in North America than that in regard to New York state.

The table (page 135) shows the general divisions of the Devonian system with subdivisions in three well-known regions of North America.

For a long time the Helderbergian series was placed with the Silurian system, but on the basis of careful study of its fossils, it is now generally agreed that it really represents the lowest portion of the Devonian system. This is a good example of the difficulty in drawing the line between two systems when no sharp stratigraphic break or unconformity exists.

As stated in connection with the preceding system, so here the reader should know that in many parts of America where definite correlations have not been made, local subdivisions or stage names are employed, and also that the lithologic character of the various stages in New York may be quite different from those in other regions.

<table>
<tr><th></th><th>General</th><th colspan="2">New York Pennsylvania</th><th>Ohio</th><th>Missouri</th></tr>
<tr><td rowspan="2">Upper Devonian</td><td>Chautauquan series</td><td>Chemung fm.</td><td rowspan="2">Catskill ss.</td><td rowspan="2">Ohio sh.</td><td></td></tr>
<tr><td>Senecan series</td><td>Portage fm.
Genesee sh.
Tully ls.</td><td>Snyder Creek sh.</td></tr>
<tr><td rowspan="2">Middle Devonian</td><td>Erian series</td><td colspan="2">Hamilton fm.
Marcellus fm.</td><td>Olentangy sh.
Delaware ls.</td><td>Callaway ls.
St. Laurent ls.
Wittenberg sh.</td></tr>
<tr><td>Ulsterian series</td><td colspan="2">Onondaga ls.
Schoharie grit</td><td>Columbus ls.</td><td>Grand Tower ls.
Clear Creek chert</td></tr>
<tr><td rowspan="2">Lower Devonian</td><td>Oriskanian series</td><td colspan="2">Esopus grit
Oriskany ss.</td><td>Detroit River fm.</td><td>Little Saline ls.</td></tr>
<tr><td>Helderbergian series</td><td colspan="2">Port Ewen ls.
New Scotland ls.
Kalkberg ls.
Coeymans ls.</td><td></td><td>Bailey ls.</td></tr>
</table>

Distribution and Description of the Rocks

General Distribution. All known areas of outcrops of Devonian strata in North America occur within the regions showing the surface distribution of Devonian, Mississippian, and Pennsylvanian strata as indicated by map, Figure 82. A comparison with the Silurian shows that, in the eastern part of the continent, these two rock systems are very similar in distribution, though the Devonian is absent from Newfoundland and is of much larger extent in New York. The only other important differences are a much larger Devonian area in the Mackenzie River region and much smaller areas in the Arctic Islands region.

It should again be borne in mind that these surface areas of Devonian rocks fall far short of indicating the actual former, or even present extent of rocks of this age, because considerable Devonian rock has been removed by erosion, and much is now buried under later formations. Thus in the Appalachians and the mountains of the western United States, the Devonian strata have been highly folded with others, so that only the outcropping edges are visible. In the Mississippi Basin, where the strata are essentially horizontal, deep well borings have proved that the Devonian strata are extensively distributed under cover of later rocks.

Lower Devonian Strata in the East. The *Helderbergian* series is very limited in its distribution, and is found almost wholly in eastern North America in three regions: (1) Maine, eastern Quebec, Nova Scotia, and New Brunswick; (2) the northern and middle Appalachians; and (3) in the lower Mississippi Valley in Oklahoma, southeastern Mis-

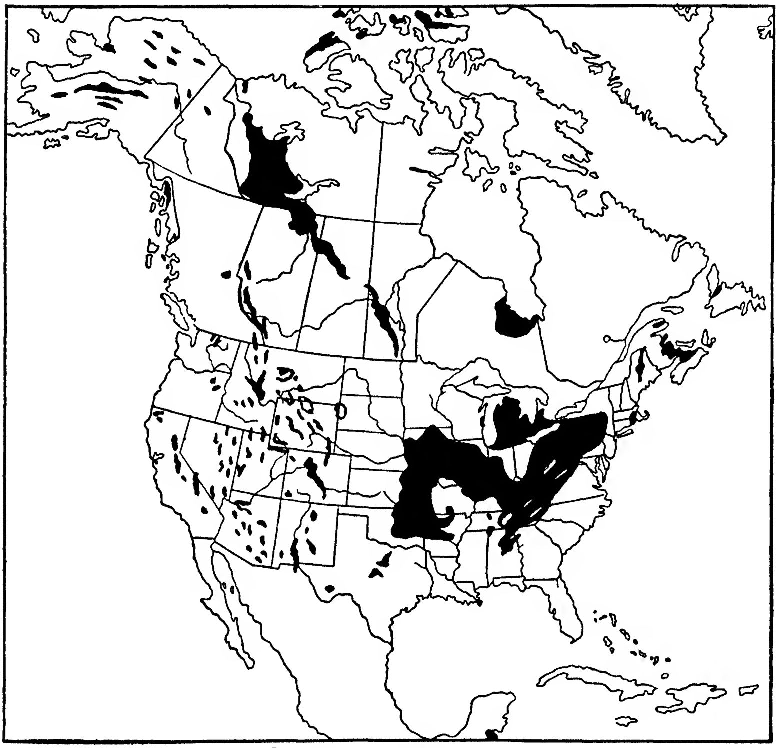


FIG. 82. Map showing known areas of outcrops (surface distribution) of Devonian, Mississippian, and Pennsylvanian strata in North America.

souri, and western Tennessee and Kentucky. Limestone almost everywhere makes up the series which ranges in thickness up to 600 feet.

The *Oriskanian* series is chiefly represented by the Oriskany sandstone, the other member of the series being only of mere local importance. The *Oriskany* formation is extensively developed from central New York southward through the Appalachian region to Alabama, and in the eastern Mississippi Valley. Its thickness varies from a few feet in New York, to several hundred feet in western Maryland. In northern

Maine, New Brunswick, and Nova Scotia, the Oriskany (much of it limestone) is well developed though not much studied.

Middle Devonian Strata in the East. The *Ulsterian* rocks, except the *Schoharie* grit which is limited to eastern New York, are much more extensive than the Lower Devonian.

The *Onondaga* limestone formation is very widespread, extending from eastern New York and eastern Pennsylvania westward to northern Michigan, and southward through Illinois, Kentucky, and Tennessee, and thence westward into Oklahoma. Its thickness is seldom over 200 feet, and it is often largely made up of corals, as for example at the Ohio River rapids near Louisville. In northern Maine, New Brunswick, and Nova Scotia, the Onondaga limestone is widespread and apparently many hundreds of feet thick. It also occurs at the south end of Hudson Bay.

The *Erian* series, represented by the *Hamilton* and *Marcellus* shales and limestones, has very much the same distribution as the Onondaga, except for the absence of Erian from the south end of Hudson Bay, and additional Erian areas in the middle Appalachians, Iowa, northern Missouri, and just west of Lake Winnipeg. In the east, shales were deposited, attaining a thickness of 1500 to 5000 feet in Pennsylvania, while in the upper Mississippi Basin, where much limestone still formed, its thickness is notably less. A good idea of the distribution (surface and concealed) of the Middle Devonian rocks is afforded by noting the water areas on the paleogeographic map (Fig. 85), though from these areas some Devonian strata have been removed by erosion.

Upper Devonian Strata in the East. These show a distribution very similar to the Middle Devonian, except that the southern Appalachians and region immediately westward also contain them. Leaving out the area of Onondaga at the south end of Hudson Bay, a good conception of the distribution of the Upper Devonian rocks may be gained by examining the map (Fig. 85), because almost everywhere that any Devonian is present, the Upper Devonian also occurs.

The *Senecan* series, except for the comparatively thin and local *Tully* limestone, consists of the *Genesee* shales, and *Portage* sandstones and shales. The Genesee ranges in thickness from a few feet in western New York to several hundred feet in central Pennsylvania, while the Portage is over 1000 feet thick in western New York.

The *Chautauquan* series of sandstones have a thickness of 1000 to 1500 feet in western New York; 3000 feet in eastern New York; and a

maximum of 10,000 feet in eastern Pennsylvania. The *Catskill* was quite certainly mostly a fresh or brackish water deposit, representing an eastern phase of the marine *Chemung* and several other Late Devonian formations.

In the Mississippi Valley, westward from New York and the Appalachians, the Upper Devonian is much thinner; subdivisions are not so well represented, or recognized; and the New York names are not used.

Devonian Strata in the West. Devonian strata outcrop more or less extensively in many parts of western North America. There is a very extensive area in the Mackenzie River Basin. Many smaller areas are in Alaska, the islands west of northern Greenland, through the Rocky Mountains of the United States and Canada, and in Arizona, Nevada, California, and other places.

The western Devonian strata are largely limestones and shales. They have been far less studied in detail and subdivided than the eastern Devonian strata.

Structure of the Devonian Strata. The Devonian strata in the Appalachian Mountains, New England, Ouachita Mountains, and the

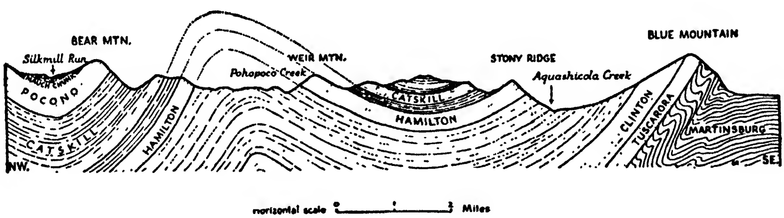


FIG. 83. A generalized geologic section showing the structure of Devonian strata (Hamilton and Catskill) and their relation to older (Silurian and Ordovician) and younger (Mississippian) formations in a part of the Appalachian Mountains in southeastern Pennsylvania. (From International Geological Congress Guidebook 7.)

mountains of western North America are usually more or less highly folded and often faulted. Elsewhere, as in western New York, the Interior Lowland, south of Hudson Bay, and the Mackenzie River Basin, the Devonian strata have seldom been more than slightly deformed.

Thickness of the Devonian System. In the northern Appalachian Mountains the Devonian system attains a maximum thickness of some 14,000 or 15,000 feet. In the southern Appalachians the thickness is usually less than 1000 feet. In New York state the system has a thick-

ness of 4000 to 7000 feet. Over much of the upper Mississippi Valley the thickness is generally less than 1000 feet, though in eastern Ohio a thickness of fully 3000 feet is reached, 2600 feet of this being Upper Devonian shales practically equivalent to the Portage and Chemung beds of the east. In Nevada the system appears to show 6000 feet of limestone and shale. In Utah the system reaches a thickness of about 5000 feet.

Igneous and Metamorphic Rocks. Both plutonic and volcanic rocks of Devonian age occur in considerable quantities in parts of New England, New Brunswick, Nova Scotia, and southeastern Quebec. Devonian volcanic rocks occur in central and southeastern Alaska. Devonian lavas occur in northern California.

In parts of New England and north to the Gulf of St. Lawrence, and also in some places in the mountains of western North America, Devonian strata have been more or less metamorphosed.

Physical History

Early Devonian. In earliest Devonian (Helderberg) time most of North America appears to have been dry land. Inspection of the paleogeographic map (Fig. 84) of that time shows that marine waters occupied a long, narrow area in the east. This sound covered the sites of the Appalachian Mountains, western New England, and the St. Lawrence Basin, connecting the last named region with the Gulf of Mexico and sending an arm of the southern Appalachian sea westward into Oklahoma. Since the Helderberg formation is chiefly limestone, the waters of this sea were clear and this implies no adjacent high lands, or at least no rapid erosion. This relatively thick and resistant formation outcrops boldly to form the "Helderberg Escarpment" extending across New York state from near Albany almost to Lake Erie. Part of the Arctic Islands region was submerged as well as some of southern Alaska.

The Oriskany sea covered much of the same regions as the Helderbergian, but it was somewhat more extensive in the east. The sharp change to deposition of coarse, clastic sediments (mostly sandstones) indicates considerable land rejuvenation, or much more rapid erosion, or both. The sediments are of distinctly shallow-water character, and the fossils show the fauna to have been suited to such conditions. The fossils are remarkably similar to those of the same age (Coblenzian) in Europe from which region they appear to have migrated. "The evidence then is fairly conclusive that during the period represented by the Coblenzian Oriskany, the arenaceous epicontinental sediment was the

ground traversed by the Coblenz fauna westward along the North Atlantic continent" (J. M. Clarke). In other words, there must have been a land connection between Europe and North America.

Middle Devonian. An outstanding feature of North American Devonian history was the more or less steady advance of marine waters

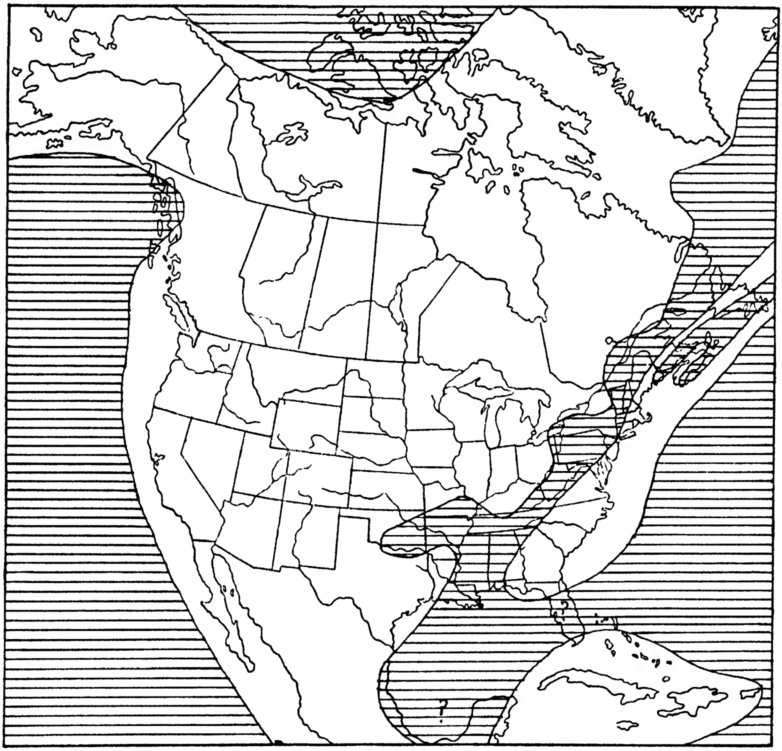


FIG. 84. Generalized paleogeographic map showing sea and land areas in North America during Early Devonian time. White areas, land; ruled areas, sea. Principal data (modified) from maps by C. Schuchert.

from the beginning of the period to beyond the middle. This marine invasion, first in the east and then in the west, reached a grand climax in late Middle Devonian (or Hamilton) time when fully 40 per cent of the continent was submerged as shown by map Fig. 85. This was one of the five or six greatest known floods in the history of North America. It should be noted that Appalachia and Canadia were connected across New England and the Upper St. Lawrence Basin.

During early Middle Devonian (Onondagan) time in eastern North America, the sea must have been mostly clear, shallow, and comparatively warm as indicated by the widespread accumulation of coralline limestone. Evidently there were no rapidly eroding lands.

Late Middle Devonian (Hamilton) time witnessed an interesting physical change probably due to a very considerable rejuvenation of

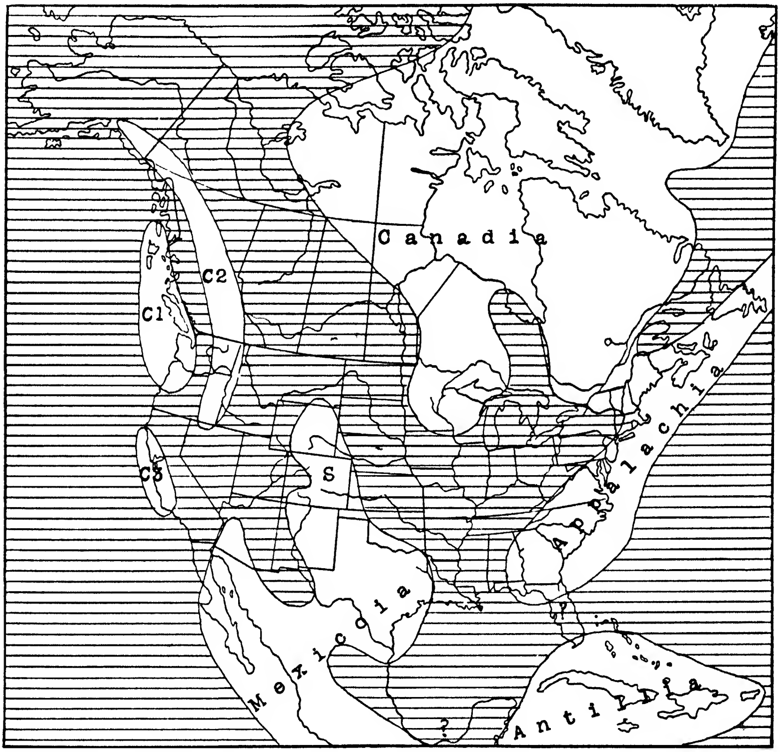


FIG. 85. Generalized paleogeographic map showing sea and land areas in North America during late Middle and early Late Devonian times. This was the greatest Devonian sea. White areas, land; ruled areas, sea. C1, C2, and C3 are parts of Cascadia, and S is Siouxia joined to Mexicoia. Principal data (modified) from maps by B. Willis, C. Schuchert, and R. Chamberlin.

northern Appalachia, resulting in renewed erosion and deposition of vast quantities of muds in the eastern part of the interior sea. These muds are now hardened and called the Marcellus and Hamilton shales. Farther westward in the Mississippi Basin, however, much limestone still formed in the clearer sea.

Late Devonian. The great sea which was so extensive in the late Middle Devonian continued to cover nearly the same areas in early Late Devonian time. Then the sea began to retire from the land, first from

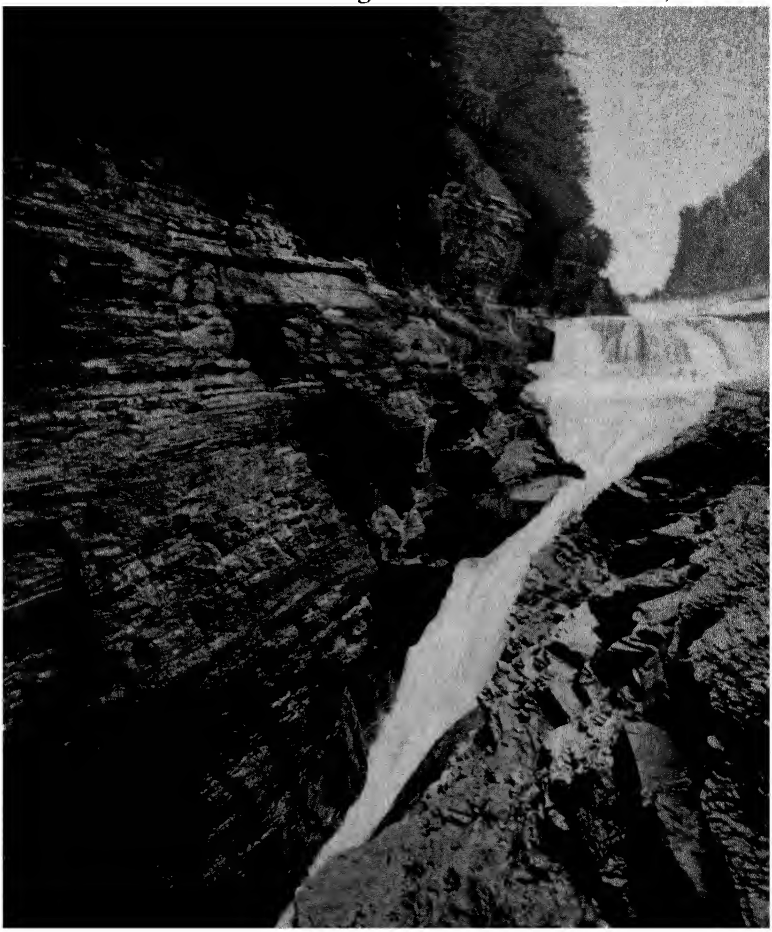


FIG. 86. Upper Devonian shales along the Genesee River in western New York. (Photo by C. Streb, courtesy of the New York State Museum.)

the east and finally from the west, leaving the whole continent, with little possible exception, dry land at the close of the period.

In southeastern New York and eastern Pennsylvania there was a tremendous accumulation of sands together with some muds during Late Devonian time. Now consolidated, these sediments comprise the Cat-

skill formation which was deposited partly under brackish water and partly as alluvial fan (or fluviatile) material. The formation reaches a thickness of 3000 feet in New York and 10,000 feet or more in Pennsylvania. The prevailing color is red to reddish brown, and its few fossils are non-marine forms. In western New York and western Pennsylvania the Catskill grades into several finer grained clastic and limy formations whose total thickness steadily diminishes westward. Quite clearly this formation is a great delta deposit (*Catskill delta*) built westward into the shallow interior sea. A large river, or possibly several rivers, from rejuvenated Appalachia supplied the sediment.

Late Devonian volcanoes were active in parts of Alaska.

Close of the Devonian (Acadian Revolution). Because the late Devonian sea withdrew almost entirely from the continent transitional Devonian-Mississippian strata are seldom found, a noteworthy exception being in Tennessee and Kentucky. In other words, the Devonian and Mississippian systems of rocks are nearly everywhere separated by an unconformity, though usually not a profound one.

Mountain-making on a large scale occurred along the Atlantic Coast from Newfoundland to North Carolina. The evidence for this orogeny is best seen in New Hampshire, Maine, and northward through the Gulf of St. Lawrence region where Devonian and older strata are much folded and intruded by igneous rocks. The elevation of the mountains so affected the northern part of the Appalachian geosyncline that Paleozoic sea water never again covered the area. Much of Appalachia must have been elevated at this time. This orogenic disturbance has been called the *Acadian Revolution,* so named from the Acadian region. The movement of folding and elevation, accompanied by igneous activity (both plutonic and volcanic), began well before the end of the period and reached a climax near its close. Succeeding Mississippian strata rest by unconformity upon the more or less upturned and eroded rocks of the region.

The rise of the Acadian Mountains no doubt so rejuvenated northern Appalachia that a large river from it produced the great Catskill delta.

Climate

The general distribution and character of the fossils, as for example the corals of the Onondaga sea, indicate rather mild and uniform climatic conditions. Possibly such red formations as the Catskill and the European "Old Red Sandstone" were formed under arid or semi-arid conditions. Glacial deposits indicate at least local glaciation in South Africa.

Economic Products

Much oil and gas are obtained from Devonian strata in the great Appalachian field (Fig. 53). This oil is of excellent quality. In southwestern New York, western Pennsylvania, and West Virginia the oil comes mostly from Upper Devonian sandstone, and in Kentucky from Middle Devonian limestone. Much gas comes from the Oriskany sandstone. Lower Devonian limestone in Oklahoma yields oil.

An important source of glass sand in the northern Appalachian Mountain region is the white Oriskany sandstone consisting of nearly pure quartz grains.

Devonian novaculite (chert) is used for grinding stones in Arkansas.

Black phosphate deposits occur in Upper Devonian shales of central Tennessee.

Devonian rocks are much used for building stone and for lime and cement manufacture in the eastern United States.

Foreign Devonian

Europe. It may be said in general that the Devonian of Europe began with a progressive transgression of the sea, continuing till near the close of the period when much of the continent was submerged.

In the southern British Isles there are thick marine strata containing much contemporaneous igneous rock (lava sheets), while in the northern portion occurs the famous "Old Red Sandstone" which is largely of continental origin. This sandstone attains a greatest thickness of fully 20,000 feet, of which 6000 feet are interbedded lavas and tuffs. Deposition of the sandstone appears to have taken place, probably partly as delta and partly as wind-blown deposits, in basins or lagoons more or less cut off from the open sea, or at times in fresh-water lakes. Fossils are not abundant, but they constitute a remarkable assemblage of land, fresh water, and marine species scattered through various horizons. In many respects the "Old Red Sandstone" is much like the Chemung-Catskill formation of America.

The typical marine strata of Germany also contain many beds of lava, thus indicating much igneous activity during the period.

In west-central Europe much of the Devonian has been metamorphosed.

Typical marine limestones, shales, and sandstones were extensively deposited in Spain, France, Switzerland, much of Austria, and Russia,

but with Lower Devonian mostly absent from Russia. Coralline limestones are prominent in the Alps.

Other Continents. The Devonian sea spread over most of Siberia and into central Asia and China. Rocks of this age are also known in various parts of southern Asia, northern and southern Africa, Australia, New Zealand, and in South America they appear to be more widespread than the rocks of any other Paleozoic system. Most of South America must have been submerged under the sea.

Important mountain-making, accompanied by batholithic intrusions, occurred in the eastern part of Australia.

CHAPTER XIV

ROCKS AND PHYSICAL HISTORY OF THE MISSISSIPPIAN

Origin of Name and Subdivisions

Formerly the Carboniferous period included all of what, in America at least, we now call the Mississippian, Pennsylvanian, and Permian periods.[1] In Europe the term Carboniferous is still employed, though the Permian has been separated from it. The name "Carboniferous" was given about one hundred years ago because it was supposed that workable coal beds were almost, if not wholly, confined to that system. Although workable coal beds are known to occur in most later systems, nevertheless what was long known as Carboniferous, particularly that portion now called Pennsylvanian, does contain the world's greatest coal deposits. The name "Mississippian" was given because of important outcrops of its formations in the eastern Mississippi Basin, especially along the river.

A good idea of the general divisions of the system, with subdivisions in four regions, may be gained from the following table:

<table>
<tr><th></th><th>General</th><th>Mississippi River States</th><th>Pennsylvania</th><th>Idaho, Utah</th><th colspan="2">Calif.</th></tr>
<tr><td rowspan="2">Upper Mississippian</td><td>Chester series</td><td>(Various limestone formations)</td><td rowspan="2">Mauch Chunk shale
Greenbrier limestone</td><td rowspan="2">Brazer limestone</td><td rowspan="4">Calaveras formation</td><td rowspan="2">Baird sh.</td></tr>
<tr><td>Meramec series</td><td>Ste. Genevieve ls.
St. Louis ls.
Salem ls.
Warsaw sh. & ls.</td></tr>
<tr><td rowspan="2">Lower Mississippian</td><td>Osage series</td><td>Keokuk ls.
Burlington ls.
Fern Glen ls.
(Chouteau ls.)</td><td rowspan="2">Pocono sandstone</td><td rowspan="2">Madison limestone</td><td rowspan="2">Bragdon fm.</td></tr>
<tr><td>Kinderhook series</td><td>Hannibal ls.
Louisiana ls.
Chattanooga sh. (Miss. ?)</td></tr>
</table>

Distribution and Description of the Rocks

General Distribution. Figure 82 shows the surface distribution of the combined Devonian, Mississippian, and Pennsylvanian strata in

[1] In its geologic folios the U. S. G. S. still uses the term Carboniferous.

North America. In the western part of the continent the Mississippian and Pennsylvanian systems often have not been satisfactorily separated. In the eastern part of the continent, however, the two systems have usually been clearly separated, and map, Fig. 87 shows the surface distribution (areas of outcrops) of the Mississippian there. A comparison with the Devonian shows that the Mississippian has a very similar surface distribution in eastern North America, and that the Mississippian generally borders the Devonian areas. This is because Devonian conditions gave way to Mississippian with no great interruption of deposition.

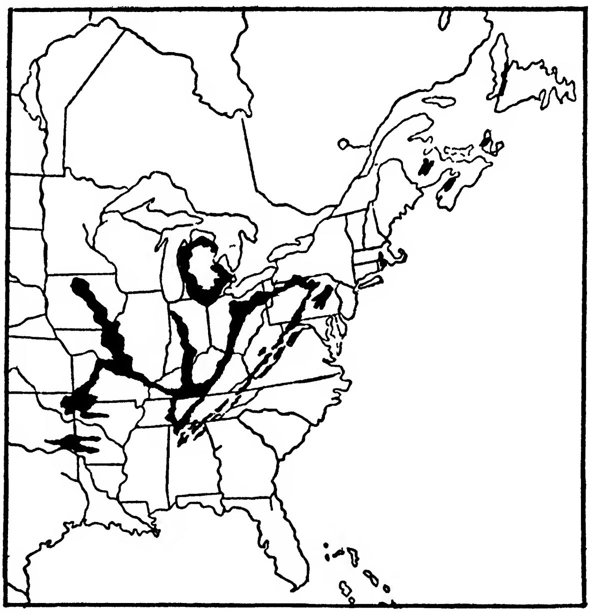


FIG. 87. Map showing the surface distribution (areas of outcrops) of Mississippian strata in eastern North America.

A distribution feature of special importance as compared with the Ordovician, Silurian, and Devonian is the complete absence of Mississippian strata from all of the northern one-half of North America east of the Rocky Mountains with the exceptions of the Gulf of St. Lawrence and Arctic Islands regions.

In the Appalachians, Rockies, and mountains still farther west, the outcropping strata form long and short, narrow belts because the rocks have been highly folded and only the eroded edges of upturned strata are visible (Fig. 87). The eastern Mississippi Basin shows a different type

of distribution because the rocks are there in nearly horizontal position and outcrop where the later (overlying) Paleozoic strata have been removed from them by erosion, or where later sediments were never deposited upon them. The character of the rocks and distribution of outcrops, supplemented by many deep well sections, proves that Mississippian strata underlie nearly the whole Mississippi Basin except the Gulf border, and Wisconsin and Minnesota.

Lower Mississippian Rocks in the East. The *Pocono* sandstone, also including some conglomerate, shale, and thin beds of coal, extends from northern Pennsylvania to Virginia in the Appalachian district. Its thickness varies from about 2000 feet in Pennsylvania to about 100 feet in the south. As judged by numerous terrestrial fossils, the Pocono appears not to be a typical marine deposit. Just west of the Appalachians considerable shale is associated with the sandstone of this same age, while in the Mississippi River states the Lower Mississippian is represented by the *Kinderhook* and *Osage* series, which contain much limestone. The Kinderhook consists of sandstone, shale, and limestone, but varies greatly in lithologic character from place to place. The *Chattanooga* (and related) shale is probably very early Mississippian, but by some it is classed as partly or wholly very Late Devonian. The Osage series directly overlies the Kinderhook, and is dominantly limestone, though with some shale. Both Kinderhook and Osage are chiefly true marine deposits. Lower Mississippian strata in southern Michigan are mostly sandstones and shales (often red), with some interbedded salt and gypsum deposits.

Upper Mississippian Rocks in the East. In the northern Appalachian district, the *Mauch Chunk* formation, consisting mostly of red sandy shales, directly overlies the Pocono, while in Maryland and West Virginia the lower portion of the Mauch Chunk gives way to the *Greenbrier* limestone. The Mauch Chunk shows a maximum thickness of 3000 feet in eastern Pennsylvania, but this diminishes notably to the north, west, and south. It is considered to be either a great flood-plain or a delta deposit. Farther west, in the Mississippi River states, the Upper Mississippian includes the *Meramec* and *Chester* series. These are made up almost wholly of limestone of very widespread extent. The *Salem* limestone in Indiana is the source of the well-known building stone called the "Bedford limestone." Mammoth Cave, Kentucky, is in Upper Mississippian limestone.

The Mississippian of Nova Scotia and New Brunswick has not been

so carefully subdivided, but it is largely sandstone below and limestone, with some red beds and gypsum, above. Its thickness reaches 5000 feet.

Mississipian of the West. This system is very widely distributed in the west as proved by the numerous exposures, but it has not been as carefully studied and subdivided as in the east. Throughout the system, which is commonly several thousand feet thick, limestone greatly predominates. A very widespread formation in the Rocky Mountains is the *Madison* limestone which reaches a thickness of 1600 feet (Fig. 88). The *Brazer* limestone, several thousand feet thick, rests upon the Madison by unconformity.

The nearly horizontal *Redwall* limestone outcrops in the sides of the

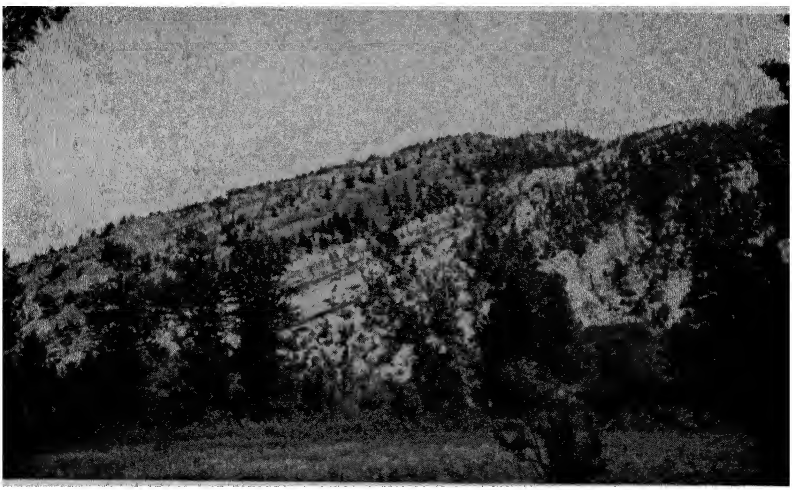


FIG. 88. A mountain of strongly tilted Lower Mississippian (Madison) limestone. About four miles south of Livingston, Montana.

Grand Canyon of Arizona for many miles in the form of a cliff 500 feet high, and stained bright red.

The *Calaveras* formation, in the Sierra Nevada Mountains, consists of a great thickness of metamorphosed sandstones, shales, limestones, and associated volcanics. It probably represents most of the Mississippian.

Structure of the Mississipian Rocks. Mississippian strata in the Appalachian Mountain region, the Gulf of St. Lawrence region, the Ouachita Mountains, and the mountains of western North America are usually more or less highly folded and often faulted.

In the great Interior Lowland, the widely occurring Mississippian strata are only slightly deformed or disturbed from their original horizontal position.

Thickness of the Mississippian. The Mississippian system in eastern North America ranges in thickness from about 5000 feet in eastern Pennsylvania to only some hundreds of feet in the western part of the same state. In the Mississippi River states the maximum thickness is 2500 feet, though it is generally less than 1000 feet. The Ouachita Mountains contain shales and limestones about two miles thick. In the western part of the continent thicknesses of several thousand feet (maximum over 5000 feet) have been observed at several places, while in other localities, as in the Black Hills and parts of Colorado, it measures only a few hundred feet thick. Five hundred feet are known in the Grand Canyon of the Colorado River.

In Nova Scotia and New Brunswick the thickness of the Mississippian strata reaches fully 5000 feet.

Igneous and Metamorphic Rocks. Mississippian volcanic rocks are widespread in Alaska. They also occur in the Klamath and Sierra Nevada Mountains of California, and in the Ouachita Mountains of Oklahoma.

The Mississippian strata in southeastern New England (*Bolton* schist?), in the Sierra Nevada Mountains (Calaveras formation), and in some other parts of the west are more or less metamorphosed.

Physical History

Earlier Mississippian. The continent was nearly all land at the opening of the Mississippian period. Disregarding certain minor shiftings of the sea, the great event of Early Mississippian time was an increasing expansion of the sea over the land until late Early Mississippian (Osage) time when about one-third of the continent was submerged. Fig. 89 shows the general relations of land and water of that time. Much of the area of the United States was covered by an unbroken expanse of shallow-sea water with wide connections with the Pacific and Arctic Oceans and the Gulf of Mexico. Canadia was very large and connected with Appalachia across New England. Cascadia and Mexicoia were well-defined as such.

During Early Mississippian time coarse clastic sediment (Pocono sandstone) was deposited along the western shore of Appalachia; "Red Beds," with interbedded salt and gypsum, formed in lagoons bordering

southern Canadia; at first black muds (Chattanooga), and then highly fossiliferous limestone (Kinderhook and Osage), accumulated in the great sea of the Mississippi Valley area; while the widespread, thick Madison limestone accumulated in the Rocky Mountain region; and part of the

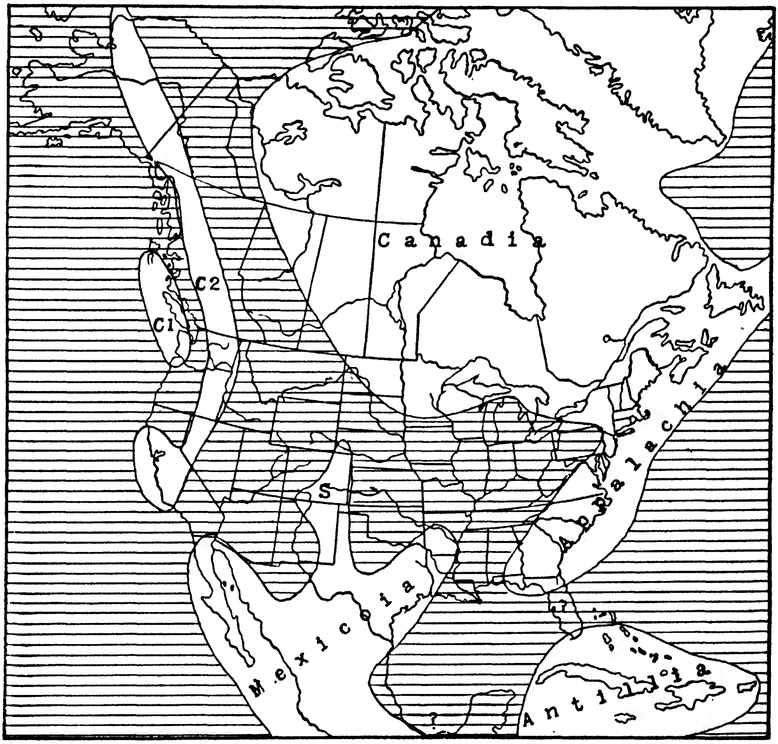


FIG. 89. Generalized paleogeographic map showing sea and land areas in North America during late Early Mississippian time. This was the greatest Mississippian sea. C1 and C2 are parts of Cascadia, and S is a remnant of Siouxia connected with Mexicoia. White areas, land; ruled areas, sea. Principal data (modified) from maps by C. Schuchert and J. Weller.

muds, sands, and limy materials of the now metamorphosed Calaveras formation were laid down in eastern California.

Later Mississippian. After the deposition of the Meramec and St. Genevieve limestones in continued widespread interior seas, there was a very considerable withdrawal of the sea, moderate in the east, but almost complete in the Rocky Mountain region.

During Late Mississippian (Chester) time there was a tendency for the waters again to spread over the late Lower Mississippian areas, but not so extensively. Thus the middle and middle-northern parts of the United States were not submerged, and the sea was more restricted over the site of the Rocky Mountains, extending over the northern portion of the latter region only in the Late Mississippian if at all.

In the Appalachian region, during Late Mississippian time, vast quantities of clastic sediments were deposited as muds (now Mauch Chunk and Pennington shales) above the Greenbrier and Maxville limestones along the western shore of Appalachia. Conditions were locally right for coal formation as proved by some coal beds in the Mauch Chunk. The interior sea, however, had clearer waters in which limestone deposition greatly prevailed. This clear sea extended westward across the United States to the Pacific Ocean. The Brazer limestone and the upper Calaveras beds were laid down in the western part of the sea.

More "Red Beds" with associated salt and gypsum continued to form in southern Michigan lagoons and in Nova Scotia.

Volcanoes were active in California and Alaska.

Close of the Mississippian (Ouachita Disturbance). The almost complete emergence of the continent at the close of the period was brought about largely without folding or tilting of the strata. In certain regions, however, there were actual mountain-making movements, though not on a large scale. Thus, a nearly east-west zone through Arkansas and Oklahoma, where a thick body of strata had accumulated during five periods of the Paleozoic, was subjected to pressure, somewhat folded, and uplifted. This involved the Ouachita and Wichita Mountains of Arkansas and Oklahoma, and hence has been called the *Ouachita Disturbance.* The same region was much more profoundly folded and elevated in the midst of the next (Pennsylvanian) period, when the real *Ouachita Revolution* occurred.

In parts of the Gulf of St. Lawrence region, the Mississippian and older rocks were more or less folded and elevated as proved by the fact that Early Pennsylvanian strata there rest upon upturned, eroded edges of Mississippian rocks. This is the same general region which was involved in the Late Devonian (or Acadian) orogeny. Also there was a general rejuvenation of Appalachia from eastern Pennsylvania southward as proved by the fact that the great Early Pennsylvanian (Pottsville) deposit of coarse, clastic sediment was derived from a newly uplifted highland region (Appalachia) just to the east. In short, there was more or

less elevation, often with folding, from Newfoundland to Alabama and thence westward into Oklahoma. The rest of the continent was elevated, but usually with little or no deformation of the rocks.

The surface of the almost wholly emergent continent was nearly everywhere notably eroded, and so the Mississippian and Pennsylvanian systems are separated by one of the most extensive and distinct unconformities in the whole Paleozoic group of rocks. For this reason

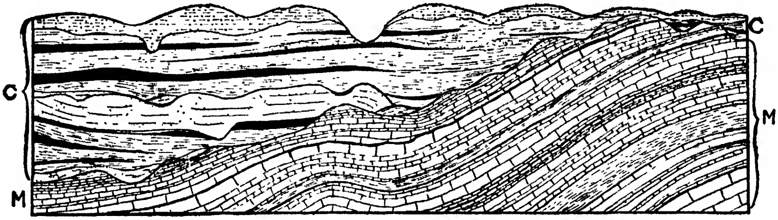


FIG. 90. Generalized section in Iowa, showing how the Pennsylvanian system (*C*) rests unconformably upon the Mississippian (*M*). (After Keyes, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

the Mississippian and Pennsylvanian should be regarded as separate systems rather than as merely subdivisions of the old Carboniferous.

CLIMATE

As for the earlier Paleozoic periods, the character and distribution of Mississippian fossils rather clearly prove absence of well-defined climatic zones like those of today. A mild, uniform climate appears to have prevailed. Salt and gypsum beds more or less associated with "Red Beds" point to arid climate in Michigan, Montana, Nova Scotia, and Australia, but these were probably local conditions. Evidence of glaciation toward the close of the period has been reported from the Ouachita region of Oklahoma, but there is some doubt about it. There is stronger evidence for glacial deposits of Mississippian age in Argentina and Australia.

ECONOMIC PRODUCTS

Considerable quantities of petroleum (oil) have been obtained from Mississippian strata in the Mid-continent, Illinois, and Appalachian fields (Fig. 53). Some gas comes from the Chester sandstone of Illinois.

Some coal is obtained from the Pocono sandstone formation of West Virginia.

Building stones of Mississippian age are much quarried, especially the *Berea* sandstone of Ohio and the oölitic so-called *Bedford* (Salem) limestone of Indiana, both of which are very widely used in the United States.

Vast quantities of salt are produced by pumping out and evaporating the natural brines from the Mississippian sandstones of Michigan, and smaller quantities from the sandstones, or limestones of Ohio, West Virgina, and Virginia.

Important zinc-ore deposits occur in the Mississippian limestones in the Joplin district of Missouri and Oklahoma, but the deposition of the ore was post-Mississippian.

Foreign (Lower Carboniferous) Mississippian[1]

Europe. As in North America, there was considerable encroachment of the sea so that much of the non-marine "Old Red Sandstone" became covered with true marine sediments. In western Europe limestone predominates. Marine waters, mostly free from land-derived sediments, extended from the western British Isles to central Germany. In these waters there lived vast numbers of organisms such as crinoids, corals, etc., the remains of which accumulated to build a great mass of limestone said to attain a thickness of 6000 feet in England, and over 2000 feet in Belgium. Farther eastward, in central Europe, shales and sandstones were laid down. In Scotland and southern England also shallow water deposits were formed. Throughout much of central, southern, and eastern Russia, chiefly non-marine materials were deposited as proved by the many coal beds and associated deposits. The rocks of Mississippian age in southern Europe are much like those of central Europe, and also the similarity of fossils shows that northern and southern Europe were not separate provinces as during most of earlier Paleozoic time.

Important crustal disturbances marked the close of the period in western Europe. As a result of folding of the rocks, mountains were formed principally as two chains—one extending from southeastern Ireland through northern France into eastern Germany, and the other from Bohemia to southern France. The structure of the remnants of these mountains, as seen in the Vosges, Harz, Black Forest, and Cornwall hills or low mountains, implies deformation intense enough to have produced high altitudes. Accompanying this deformation there were abundant intrusions and extrusions of igneous rocks. In many other parts of Europe

[1] It should be remembered that the term "Mississippian" is not used in Europe.

there were relative changes of level bewteen land and sea without very appreciable folding or tilting of the strata. Thus, the reason for separating the old Carboniferous into two systems applies with great force to Europe as well as to North America.

Other Countries. In South America Mississippian rocks are known in Argentina where they contain some coal, in Chile, and in other parts of the continent where they have not been carefully separated from the Pennsylvanian (Upper Carboniferous).

Eastern Australia, New Zealand, and Tasmania contain marine strata of Mississippian age which were generally highly deformed toward the close of the period, and injected with igneous rocks. Salt and gypsum occur in the system in western Australia.

In northern Africa the system is extensively represented, especially by limestone. Non-marine formations occur in southern Africa.

Rocks of Mississippian age are also known to be widely developed in Asia.

CHAPTER XV

ROCKS AND PHYSICAL HISTORY OF THE PENNSYLVANIAN

Origin of Name and Subdivisions

As stated in the preceding chapter, the Pennsylvanian system represents a part of what was formerly known as the Carboniferous system in America. In other continents, strata equivalent to the Pennsylvanian are usually called Upper Carboniferous. Rocks of Pennsylvanian age include the Coal Measures proper of the old Carboniferous, and they contain a far greater supply of workable coal than the rocks of any other system. The name has been given because of the typical development of the system with its coal in Pennsylvania. Subdivisions in widely separated areas are shown in the following table:

	Eastern United States	*Central Texas*	*Iowa and N. Missouri*	*S. E. Idaho*
Pennsylvanian System	4. Monongahela series (Various strata with much coal)	Cisco series (Sh., ss., coal)	Missouri series (Various strata with coal)	Wells (Limestone)
	3. Conemaugh series (Various strata with little coal.)	Canyon series (Sh., ss., ls.)		
	2. Allegheny series (Various strata with much coal.)	Strawn series (Sh., ss., ls., coal)	Des Moines series (Various strata with coal.)	
	1. Pottsville series (Various strata with some coal.)	Bend series (Ls , sh.)		
	(Absent)	(Absent)	(Absent)	

Distribution and Description of the Rocks

General Distribution. Only in the eastern part of the continent have the Mississippian and Pennsylvanian rocks been satisfactorily

separated. The accompanying map (Fig. 91) shows the surface distribution of the Pennsylvanian in Eastern North America. Two points of difference as compared with the older systems in this portion of the continent are worthy of mention as follows: (1) The Pennsylvanian rocks occupy distinctly larger (surface) areas of the Mississippi Valley-

FIG. 91. Map showing the surface distribution (areas of outcrops) of Pennsylvanian rocks in eastern North America.

Appalachian region than the rocks of any older Paleozoic system, and (2) "the commonest position for the outcrops of the preceding Paleozoic systems severally is around the outcrops of the older systems. But the outcrops of the Pennsylvanian exhibit no tendency to a similar concentric distribution. Rather do they seem to cover areas between the outcrops of the older systems" (Chamberlin and Salisbury). The reason for such differences is not far to seek. For instance Ordovician rocks are actually more widespread than the Pennsylvanian, but they are largely concealed under later rocks, while the Pennsylvanian rocks were never extensively covered by later deposits (except Glacial drift and to a small extent by Permian strata in the Appalachian dis-

trict). Shortly after their deposition, toward the close of the Paleozoic, the region was elevated and has remained a land area ever since. Post-Paleozoic erosion has been sufficient to remove much of the Permian and some of the Pennsylvanian, though large areas of the latter rocks still remain as shown on the accompanying map (Fig. 91).

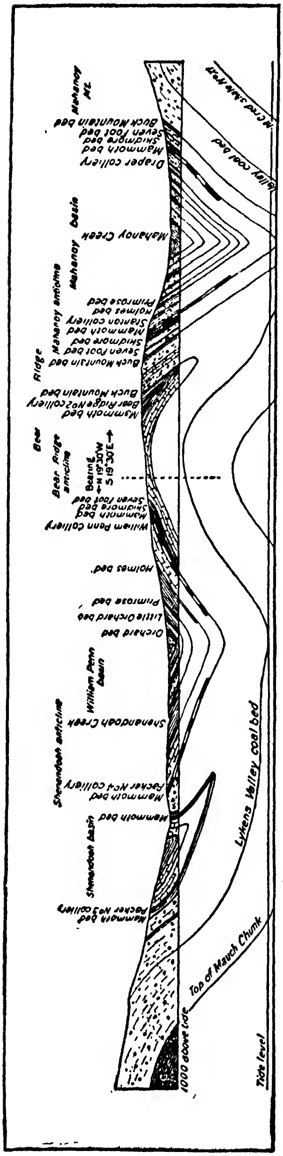


Fig. 92. Geologic structure section through one of the anthracite coal fields of eastern Pennsylvania. Note the number and thickness of the coal beds shown by the heavy black lines, and their sharply folded structure. Length of section, a little over two miles. (After Stoek, U. S. Geological Survey, 22nd An. Rep.)

Pennsylvanian rocks occur in numerous areas in western North America from northern Mexico to central Alaska, particularly in the western interior of the United States. Because they are much folded, and faulted, their areas of outcrops are comparatively small.

Pennsylvanian Rocks in the East. Rocks comprising this system in the eastern part of North America are partly of marine and partly of non-marine origin with the latter (including coal) unusually prominently developed.

The following extracts from a paper by D. White concisely describe the Pennsylvanian rocks of the Appalachian province (also see Fig. 93): "The *Pottsville,* like the succeeding formations, is composed of sandstones, shales, and clays (including fire clays, coals, and limestones), but it contains a larger proportion of sandstones and arenaceous shales than the later formations. . . . The Pottsville is thickest in the southern exposures, where, near the eastern outcrops, it probably exceeds 7500 feet. In the northwestern bituminous area . . . it measures locally less than 200 feet. . . .

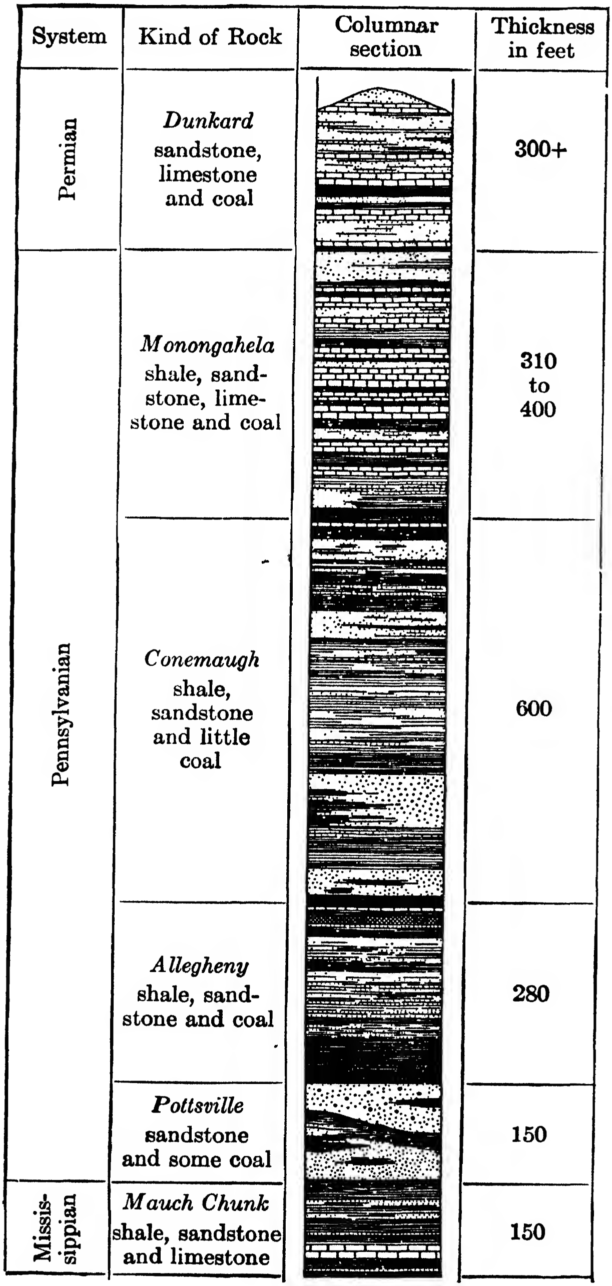


FIG. 93. Geologic (columnar) section in western Pennsylvania showing the vertical distribution of coal beds (heavy black bands) and their relations to associated strata. (After Campbell, U. S. Geological Survey, Folio 94.)

The Pottsville contains all the workable coals south of the Kentucky-Tennessee state line.

"The *Allegheny,* next succeeding the Pottsville, is a thin formation characterized by a larger proportion of coal, shale, limestone, and iron ore. In the bituminous districts . . . the Allegheny ranges generally between 250 and 350 feet in thickness near the northern outcrop, though it thins southwestward to 160 feet in northeastern Kentucky.

"The *Conemaugh* (maximum thickness, 900 feet), which succeeds the Allegheny, is generally marked at its base by sandstone or conglomerate. It is especially characterized by sandstones, shales, and limestones, intermingled, particularly in the western area, with red and green shales, clays, and sandstones. It contains less coal than any of the other Pennsylvanian formations of the Appalachian trough.

"The *Monongahela* is distinguished by its relatively large proportion of coal and limestone, the latter composing over one-third in some districts. The formation . . . averages about 325 feet or less in thickness. Its coals, including the great Pittsburgh coal at its base, are of notable thickness and value."

The four distinct subdivisions of the system above described are generally not recognized as such in the western interior lowland, but various local names are there given to the subdivisions of the system which is usually thinner and less arenaceous than in the Appalachian district. The general terms *Des Moines* series and *Missouri* series correspond roughly with the lower and upper parts of the Pennsylvanian system as shown in the preceding table.

Some areas of Pennsylvanian metamorphosed sedimentary rocks, together with some graphitic coal, occur in Rhode Island and eastern Massachusetts.

Coal-bearing strata of this age, largely shales and sandstones of non-marine origin, attain a thickness of thousands of feet in New Brunswick and Nova Scotia.

In the midst of the Mississippi Basin, especially from Indiana westward to eastern Nebraska and thence southward into Texas, alternating, continental, coal-bearing, and marine strata occur. Not only are these strata as a rule thicker, but also they are more generally of marine origin, than the Pennsylvanian strata of the Appalachian region. Sandstones and shales of this age are phenomenally developed with a thickness of several miles in Arkansas and Oklahoma.

In central Texas the various divisions of Pennsylvanian age form

a nearly complete system. These are listed in the table on a preceding page.

Pennsylvanian Rocks in the West. In the Rocky Mountains and westward in the United States, the Pennsylvanian rocks are very largely of true marine character, consisting mostly of shales, sandstones, limestones, and some metamorphosed strata. In marked contrast with the rocks of the system in eastern North America, there is little coal of this age in the west, some occurring in Alaska. The thick *Wells* limestone formation of southeastern Idaho; the very thick *Oquirrh* limestone-quartzite

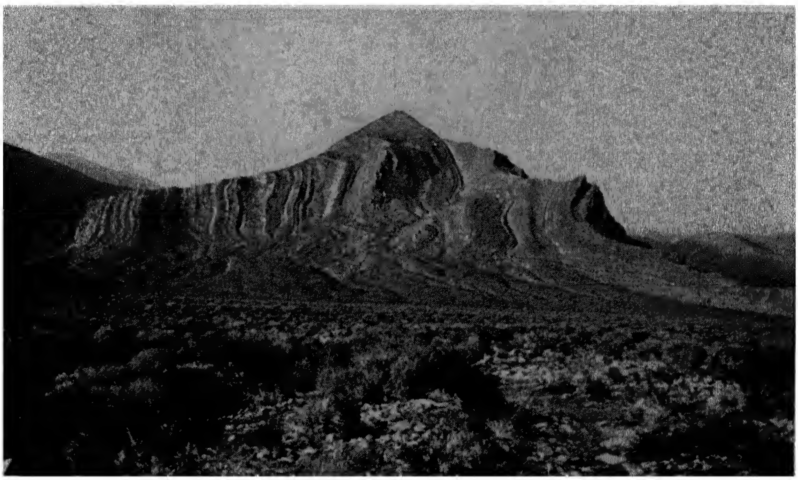


FIG. 94. A mountain of Pennsylvanian (?) marine limestone. The nearly vertical beds show a thickness of fully 2000 feet. Southern part of Panamint Mountains, California.

formation of northern Utah; and the *Fountain* red sandstone of Colorado, are particularly noteworthy.

Structure of the Pennsylvanian Rocks. In the Appalachian Mountains (Fig. 92), the Ouachita Mountains (Fig. 99), the Gulf of St. Lawrence region, southeastern New England, and the mountains of the west, the Pennsylvanian strata are usually strongly folded or tilted, and often faulted. In the great Mississippi Basin, between the Appalachian and Rocky Mountains, the strata of the system for most part lie in almost horizontal position not far above their place of origin.

Thickness of the Pennsylvanian. In the Appalachian district, the system ranges in thickness from about 1500 feet to approximately

10,000 feet. A maximum thickness of 13,000 feet is known in Nova Scotia, and 12,000 feet in Rhode Island. Through the Mississippi Basin the thickness is usually not more than 1000 to 2000 feet, though

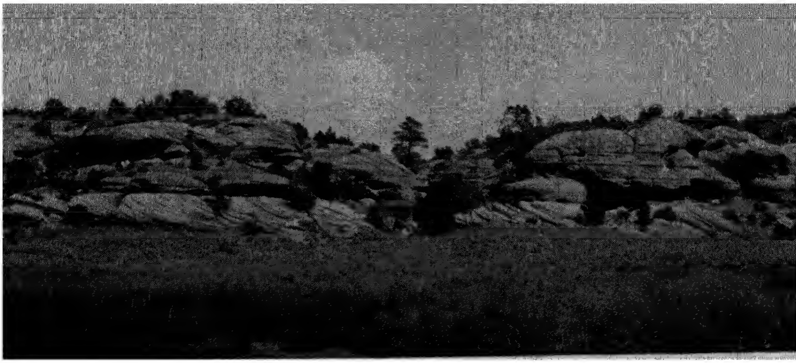


FIG. 95. Cross-bedded Pennsylvanian sandstone. Tensleep Canyon, Wyoming. (Photo by N. H. Darton, U. S. Geological Survey.)

FIG. 96. An exposure of Pennsylvanian red sandstone with beds standing in nearly vertical position. Garden of the Gods, Colorado.

in Arkansas a thickness of over 15,000 feet has been found. In the western United States the thickness varies much, though it is often at least several thousand feet. The nearly complete system in central Texas is over 5000 feet thick.

Igneous and Metamorphic Rocks. Plutonic rocks definitely known to be of Pennsylvanian age are practically absent from North America. On the Pacific Coast from northern California to Alaska, volcanic rocks, occurring in both the Mississippian and Permian systems, are not definitely known in the Pennsylvanian.

Notably metamorphosed Pennsylvanian strata (e.g. *Roxbury* conglomerate) occur in southeastern New England and locally in the mountains of the west.

Physical History

Early Pennsylvanian. The Pennsylvanian period was characterized not only by an unusual number of oscillations between land and sea, but also by various diastrophic movements more or less of the nature of mountain-making. Disregarding relatively minor oscillations of level between land and sea, the outstanding feature in regard to the relations of land and water during Pennsylvanian time was progressive submergence of a considerable portion of the continent, beginning in the east and spreading westward and then northwestward to Alaska.

As mentioned in the preceding chapter, the Mississippian period ended with a widespread emergence of nearly all of the submerged areas in eastern North America. Very early in the Pennsylvanian the sea began to transgress over the land by extending a long, narrow estuary northward through the Appalachian district as far as Pennsylvania. The Pottsville sandstones and conglomerates, derived by erosion from Appalachia immediately to the east, were deposited to great thickness in this estuary, and it is thus readily seen why the Pottsville should be thickest on the east side. Gradually the early Pottsville basin of deposition expanded and extended over much of the interior region containing Pennsylvanian coal, through central Texas, and westward across northern Mexico to the Pacific Ocean. There was probably a narrow eastern connection with the Gulf of Mexico. The marine waters, particularly in the east, were often intermittent with low swampy lands with conditions favorable for growth and accumulation of considerable plant material later to become coal.

In the Gulf of St. Lawrence and southeastern New England areas, non-marine deposition of both sediments and plant materials occurred.

Middle Pennsylvanian. The relations of land and sea much as just described continued into early Middle Pennsylvanian (early Alle-

gheny) time, and the sea gradually expanded to the late Middle of the period (early Conemaugh time). This was the greatest Pennsylvanian sea and it covered nearly one-third of the continent (Fig. 97). The vast sea swept from the Appalachian region westward over much of the United

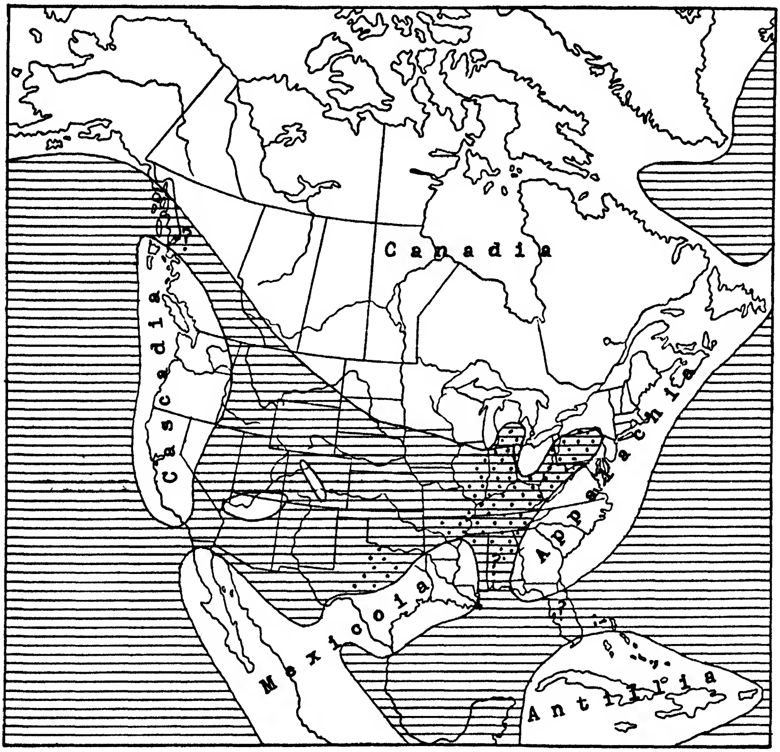


FIG. 97. Generalized paleogeographic map showing the sea and land areas in North America during Middle Pennsylvanian time. White areas, land; ruled areas, sea. This was the greatest Pennsylvanian sea. The dotted areas show alternating sea and land conditions in the Appalachian-Interior Lowland region, and non-marine deposition occurred in parts of southeastern New England and Gulf of St. Lawrence regions. Coal-producing plants thrived in these areas. Principal data (modified) from maps by B. Willis, J. Weller, and C. Schuchert.

States to Cascadia, with Pacific connections through southern California and probably through southern Alaska. An eastern marine connection with the Gulf of Mexico is doubtful. Coal-producing land plants thrived from time to time in the east, but true marine conditions prevailed over the western region. That a large island existed in northern

Arizona is proved by the absence of Pennsylvanian strata between the Mississippian and Permian, as, for example, in the Grand Canyon.

Late Pennsylvanian. The latter part of the period (Monongahela time) was marked by a great restriction of the sea as shown by Figure 98. This sea gradually withdrew almost entirely by the end of

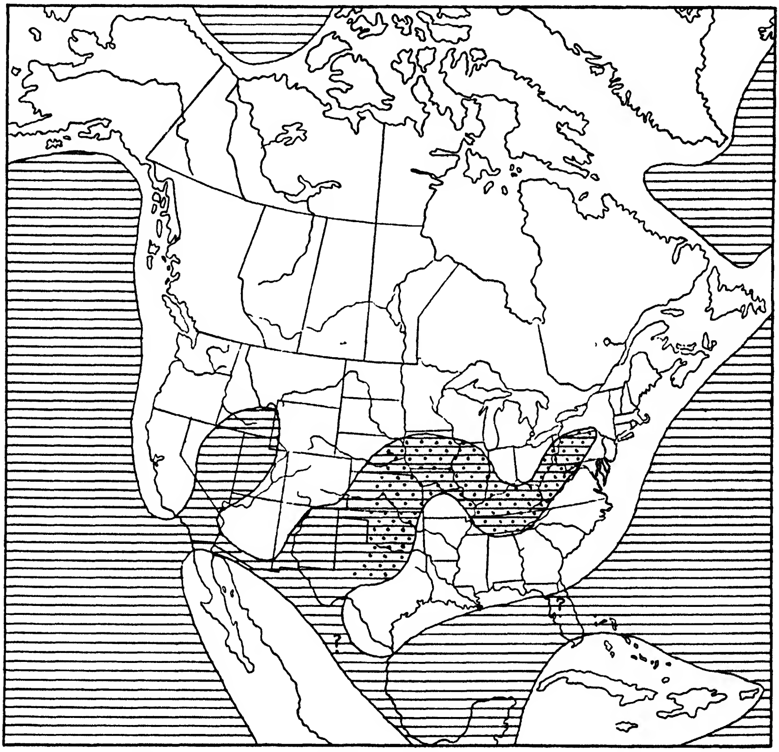


FIG. 98. Generalized paleogeographic map showing sea and land areas in North America during Late Pennsylvanian time. White areas, land; ruled areas, sea; dotted areas, as in Figure 97. Principal data (modified) from maps by C. Schuchert.

the period, thus leaving the continent practically all land. In the eastern United States marine, estuarine, lacustrine, and marsh and bog conditions alternated in most of the basin of deposition, and there were prolific and extensive growths of coal-producing plants.

In Nova Scotia non-marine sediments and vegetable materials were deposited.

Origin of the Coal Beds. Since the remarkable physical geography conditions of Pennsylvanian time favored the accumulation of the world's greatest coal beds, they deserve more detailed discussion. "Perhaps the most perfect resemblance to coal-forming condition is that now found on such coastal plains as that of southern Florida and the Dismal Swamp of Virginia and North Carolina. Both of these areas are very level, though with slight depressions in which there is either standing water or swamp condition. In both regions there is such general interference with free drainage that there are extensive areas of swamp, and in both there are beds of vegetable accumulations. In each of these areas there is a general absence of sediment and therefore a marked variety of vegetable deposit. If either of these areas were submerged beneath the sea, the vegetable remains would be buried and a further step made toward the formation of a coal bed. Reëlevation, making a coastal plain, would permit the accumulation of another coal bed above the first, and this process might be continued again and again."[1] It is, however, not necessary to assume repeated elevation and subsidence of swamp areas in order to account for numerous coal beds one above another in a given region. A general subsidence, often intermittent (with possibly some upward movements), would occasionally cause the luxuriant vegetation of a great swamp area to be killed and allow the deposition of sediment over the site. Then the filling of the shallow water with sediment would allow another bog to be formed, etc. In the coal field of Nova Scotia there are 76 distinct coal beds; in Alabama 35; in Pennsylvania at least 20; and in Illinois 9. Each of these coal beds represents an ancient swamp in which grew a luxuriant vegetation. It should be borne in mind that workable coal seams constitute only about 2 per cent of the containing strata which are sandstones, shales, clays, and, in some localities, limestones.

Perhaps no single coal seam in the world underlies such a large area (12,000 to 15,000 square miles) as the famous Pittsburgh coal bed. It is worked over an area of about 6000 square miles, and for 2000 square miles it averages 7 feet in thickness. Most of the swamps or bogs of Pennsylvanian time were much smaller than this.

In the anthracite coal district of eastern Pennsylvania, the famous "Mammoth" coal bed is remarkable for its great thickness up to 50 or more feet.

It may be of interest to consider the length of time necessary for

[1] H. Ries: *Economic Geology*, 1910, p. 9.

the accumulation of so many coal beds one above the other. A vigorous growth of vegetable matter on an acre has been estimated to produce the equivalent of 100 tons of dried organic matter per century. This amount compressed to the specific gravity (1.4) of coal would cover an acre less than two-thirds of an inch deep. Considering that four-fifths of the organic matter escapes as gases in the process of coal making, we find that it would take nearly 10,000 years to make one foot of coal. Now, since the total thickness of coal beds in the Pennsylvanian system is often from 100 to 250 feet, it is readily seen, on this basis, that the time necessary for the accumulation of the coal deposits was from 1,000,000 to 2,500,000 years. The duration of the Pennsylvanian period was of course much longer than that.

Ouachita Revolution. Mention has already been made of the so-called Ouachita Disturbance toward the close of the Mississippian

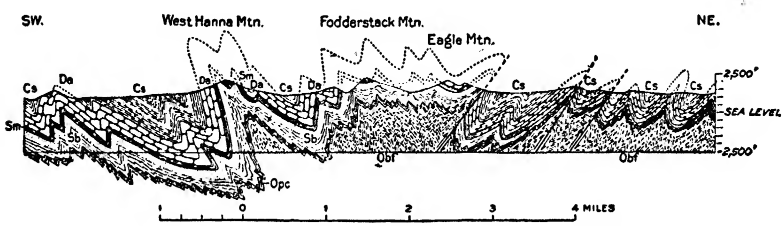


FIG. 99. Structure section through part of the southern Ouachita Mountains, near Shady, Arkansas. *Obf, Opc* = Ordovician; *Sb, Sm* = Silurian; *Da* = Devonian; and *Cs* = Late Mississippian. (After Miser and Purdue, U. S. Geological Survey.)

period when the Ouachita Mountain region of Arkansas and Oklahoma was somewhat folded and elevated. According to H. D. Miser, however, "the 25,000 feet of exposed strata of Paleozoic age in the Ouachita Mountains were subjected to great compressive movements during the middle or later part of the Pennsylvanian." The strata were then highly deformed, often with development of overturned folds and thrust faults, as shown in the accompanying structure section (Fig. 99). This was the real *Ouachita Revolution,* resulting in a mountain range with an east-west trend.

The so-called Ancestral Rockies extended from northern New Mexico through Colorado into southern Wyoming. The fact that both the Pennsylvanian and Permian sediments flanking the area contain so much coarse land-derived material, ranging from coarse sandstone to

boulder conglomerate, shows that the source area of these sediments must have been mountainous, and that it existed throughout most of Pennsylvanian and Permian times (Fig. 105). The region of the Ancestral Rockies was uplifted or rejuvenated more than once, with particularly pronounced uplifts in Early and Late Pennsylvanian times.

In the Marathon region of western Texas the Pennsylvanian and older strata were much folded and faulted toward the close of the Pennsylvanian period as proved by the fact that little deformed Permian strata there rest by unconformity upon highly deformed Pennsylvanian strata. This has been called the *Marathon Disturbance.*

Climate

Many years ago the plant life of the great coal period was thought to imply a warm to tropical, very moist, uniform climate. More careful study, however, clearly points to a temperate, only relatively humid, but remarkably uniform climate. Some of the criteria favoring this latter view may be stated as follows: [1] The great size and height of the plants together with their frequent succulent nature and spongy leaves indicate luxuriant growth in a moist, mild climate; absence of annual rings of growth shows absence of distinct change of seasons; the presence of aërial roots, by analogy with similar modern plants, implies a moist and warm climate; the nearest present-day allies of the coal plants attain greatest growth in warm and humid climates; at present the greatest accumulations of vegetable matter in bogs and marshes take place in temperate climates where decay is not too rapid and thus suggests a similar climate for the accumulation of the coal deposits; and the remarkable distribution of almost identical plant types in Pennsylvanian rocks from Arctic to tropical regions clearly shows a pronounced uniformity of climate over the earth.

Economic Products

As already suggested, the principal economic product of Pennsylvanian age is coal, the richest and most extensive coal deposits in the world being of this age. Eastern North America, western Europe, and northern China contain the most important coal fields. The map (Fig. 100) gives a general idea of the locations of the coal fields of the eastern United States. All the solid black areas east of the Rocky Mountains, excepting the very small ones in Virginia and North Carolina, repre-

[1] Based upon the work of D. White: *Jour. Geol.,* Vol. 17, 1909, p. 338.

sent fields of Pennsylvanian coal. The areas largely underlain with beds of workable coal are as follows: (1) Anthracite field of eastern Pennsylvania—484 square miles; (2) Appalachian field from western Pennsylvania to Alabama—70,000 square miles; (3) Eastern Interior field in Indiana, Illinois, and Kentucky—50,000 square miles; (4) Northern Interior field in Michigan—11,000 square miles; (5) Western Interior field from Iowa to Oklahoma—72,000 square miles; (6) Texas field—13,000 square miles; and (7) Nova Scotia-New Brunswick field—18,000 square miles. Thus in eastern North America a total of about 235,000 square miles is mostly underlain with workable coal of Pennsylvanian age. Considerable coal of this age also occurs in Alaska.

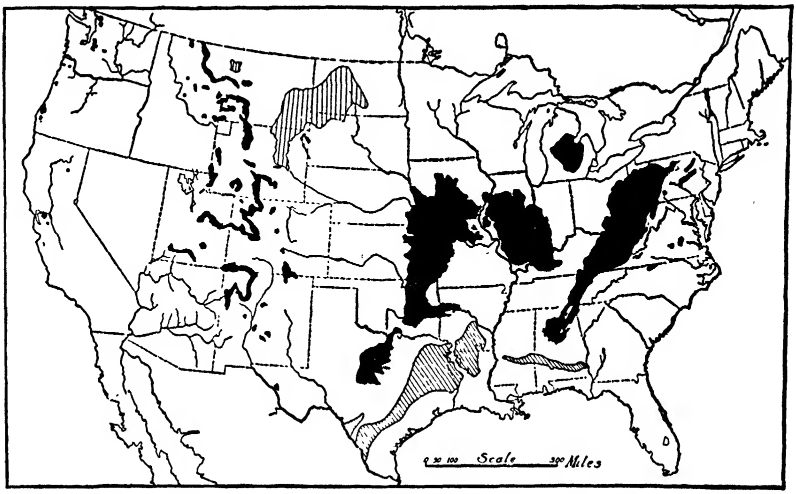


FIG. 100. Map of the United States showing the principal coal fields. The lined areas represent lignitic coals. All solid black areas east of the Rocky Mountains, excepting the very small ones of Triassic age in Virginia and North Carolina, represent fields of Pennsylvanian coal. All coal in the western United States is Cretaceous and Tertiary. (Modified after U. S. Geological Survey.)

Iron ores of some importance are found in the carbonate and oxide forms as bedded deposits in Pennsylvanian rocks. Such deposits were formed by precipitation, in the marshes and swamps, of the iron brought down from the lands in soluble form. The principal deposits occur in western Pennsylvania, eastern Ohio, and northern West Virginia.

Pennsylvanian rocks also yield much oil and gas especially in the

Mid-continent field of Kansas, Oklahoma, and Texas, and in Ohio, Indiana, Illinois, and Kentucky. Some oil also occurs in rocks of this age in Wyoming, Utah, and New Mexico.

Pennsylvanian limestone and shale are much used in making Portland cement, and shale in the manufacture of ceramic products, in the eastern United States.

Foreign Pennsylvanian

Europe. Viewed in a broad way, the Pennsylvanian of Europe presents certain interesting parallels with North America. Thus in Europe, sandstone or conglomerate, corresponding to our Pottsville, often lies at the base of the system. Above this, in western Europe, are the Coal Measures consisting of shales, sandstones, and some limestones together with numerous beds of coal, and in every way much like the Coal Measures of eastern North America. In eastern and southern Europe the rocks are largely true marine limestones and free from coal, though some coal does exist in southern Russia.

Mountain-making which, during Late Mississippian time, involved parts of central and western Europe, including southeastern Ireland and England, parts of northern and southern France, and much of Germany, was renewed with great intensity during Late Pennsylvanian time.

Other Continents. Much rock of Pennsylvanian age, both of marine and non-marine origin, occurs in Asia, with coal beds in Asia Minor, the east side of the Ural Mountains, and in northern China. The coal beds of China are extensive and important.

Marine strata without coal occur in northern Africa. In the Zambesi district of southern Africa a coal field is known.

In Australia and South America marine and non-marine strata of this age are also rather widespread. Much coal occurs in southern Brazil.

CHAPTER XVI

ROCKS AND PHYSICAL HISTORY OF THE PERMIAN

ORIGIN OF NAME AND SUBDIVISIONS

THIS period was so named by Murchison in 1841 because of the widespread development of rocks of this age in the Russian province of Perm. It is rather distinctly a transition period between Paleozoic and Mesozoic eras. In both the eastern and western United States the Pennsylvanian and Permian strata are usually not sharply separated, while in the western interior region the Permian and Triassic strata are often much alike. Thus it is often difficult to definitely separate the Permian from the systems immediately above and below it. The scarcity or absence of fossils in many of the western areas add to the difficulty. The Permian system is especially well-developed in Texas.

The following table will give a general idea of the subdivisions now recognized in some of the better known regions, though it must be clearly understood that precise correlations are not meant to be implied.

	Central Texas	Western Texas	Kansas	Grand Canyon	W. Va.
PERMIAN SYSTEM	(Missing)	Bissett cg. Capitan ls., sh.	(Missing)	(Missing)	(Missing)
	Double Mountain "Red Beds", ls., salt, gypsum. Clear Fork ls., sh., salt	Word ls., sh. Leonard sh. Hess ls.,	Cimarron "Red Beds", gypsum. Big Blue sh., ls, salt beds (near top).	Kaibab ls., Coconino ss. Hermit sh. Supai ss., sh.	Dunkard ss., sh., coal.
	Wichita ls.. "Red Beds".	Wolfcamp sh.			

DISTRIBUTION AND DESCRIPTION OF THE ROCKS

General Distribution. Compared with the preceding Paleozoic systems, Permian strata occur almost entirely in the western one-half of North America (Fig. 101). Permian plutonic rocks are, however, abundantly represented on the Atlantic Coast from Newfoundland to Alabama (Fig. 162). There are small areas of Permian strata in the Gulf of St. Lawrence region; a small one in southeastern New England;

a larger one in Pennsylvania, Ohio, and West Virginia; large areas in Arizona, New Mexico, Texas, Oklahoma, and Kansas; and numerous smaller areas in Colorado, Utah, Nevada, California, Idaho, Montana, Wyoming, western Canada, Alaska, and the Arctic Islands.

In the western United States the Permian strata are considerably more extensive than their surface distribution because they are con-

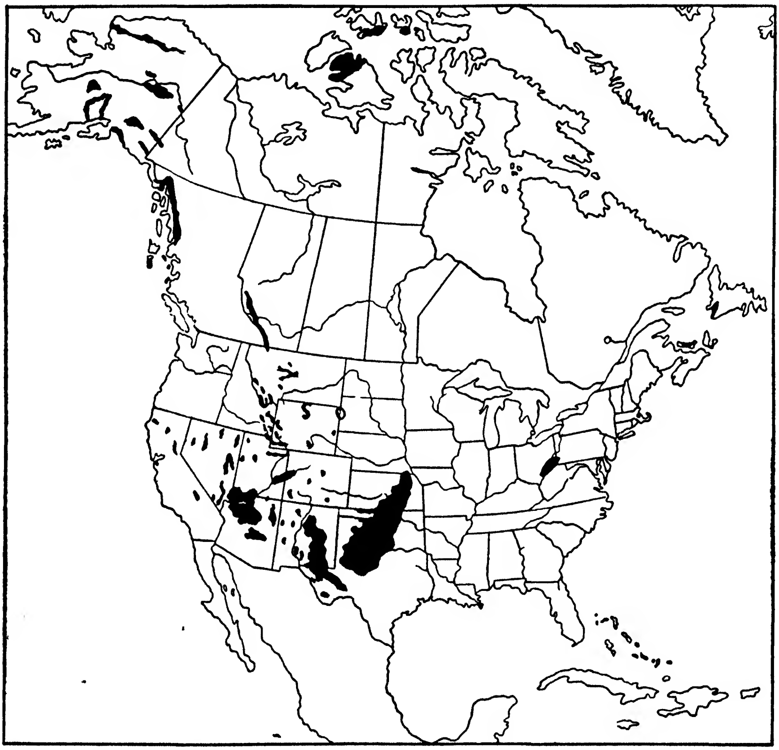


FIG. 101. Map showing known areas of outcrops (surface distribution) of Permian strata in North America.

cealed under Mesozoic or Cenozoic rocks over large areas. Also there is some reason to think that the Permian strata formerly extended over much of the Great Basin region, but have been removed by erosion, leaving much Pennsylvanian or Mississippian rock now at the surface. In the eastern United States, however, the few small areas shown on the map (Fig. 101) comprise all of the Permian except possibly some in the lower Mississippi Valley where Mesozoic and later rocks effectually conceal the older rocks.

Description of the Rocks. The Permian strata (*Dunkard* series) in the small area of the northern Appalachian Plateau district are sandstones and shales, together with some limestone and coal beds. They are in every way much like the Coal Measures just below. Middle and Upper Permian are absent.

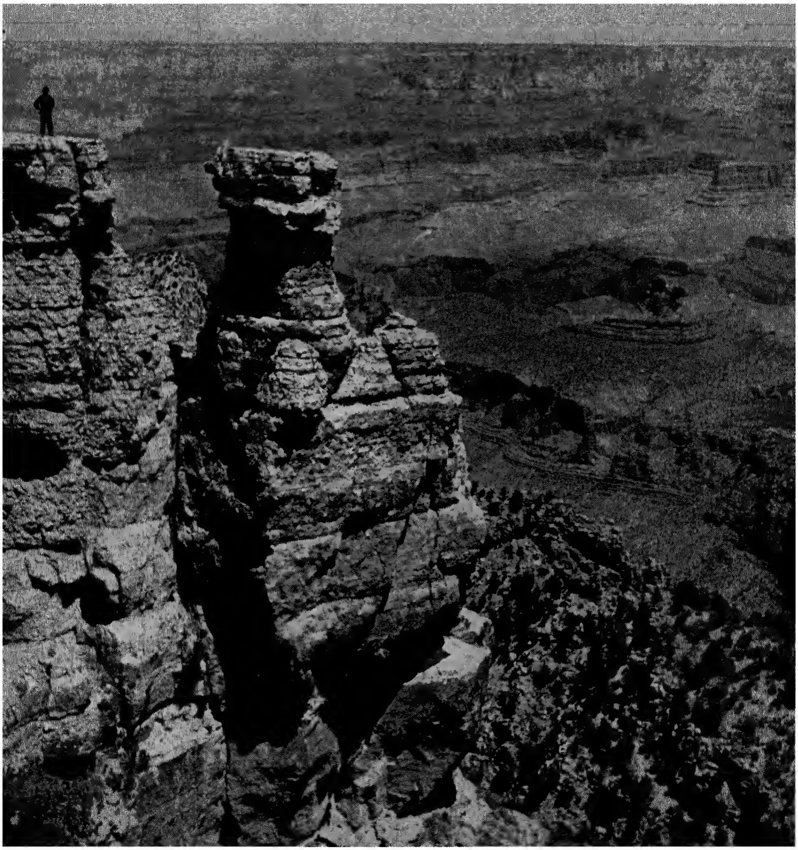


FIG. 102. A detail view of Permian (Kaibab) marine limestone at the rim of the Grand Canyon of Arizona. Most of the rock in the distance is of Paleozoic age. (Courtesy of the U. S. Geological Survey.)

In Kansas the Permian rocks are divisible into the *Big Blue* series, consisting of shales and limestones (largely marine) in the lower part and shales and salt beds in the upper part, and the overlying *Cimarron* series of red sandstones, shales, and gypsum beds, mostly non-marine. The Upper Permian is there missing.

The Permian strata of central Texas are divisible into three series as shown in the above table. Limestones and "Red Beds" largely constitute the *Wichita* series, and red shales, limestones, salt, and gypsum chiefly make up the *Clear Fork* and *Double Mountain* series. Upper Permian strata are missing.

The Middle Permian salt beds of Kansas, Oklahoma, and Texas underlie an area of fully 100,000 square miles, reaching a total thickness of more than 1000 feet in Texas (Fig. 104).

In the Permian of Texas, potash deposits of considerable extent and probable commercial value have been found.

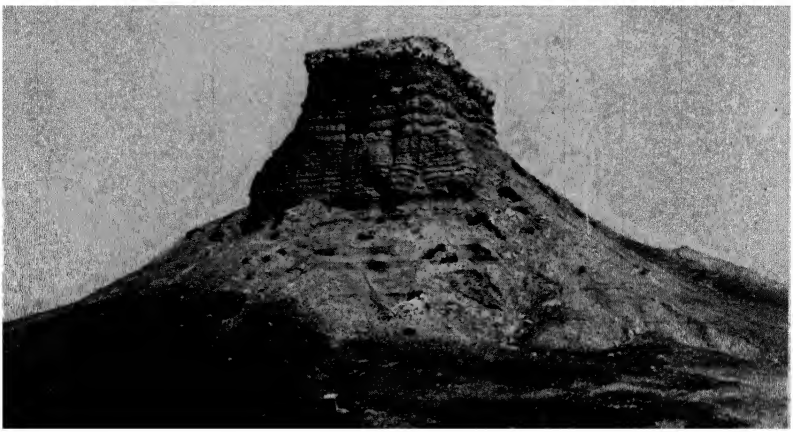


FIG. 103. Late Permian or early Triassic "Red Beds" in Red Butte, eastern Wyoming. The bright red strata are capped by a 30-foot layer of white gypsum. (After Darton, U. S. Geological Survey, Folio 127.)

Western Texas and southeastern New Mexico contain what is probably the most complete set of Permian strata known in North America. Even the Upper Permian is there represented. The section shows fully 14,000 feet of marine strata, largely limestones and shales. Some conglomerates also occur, especially at the top (*Bissett* conglomerate).

Strata, mostly of non-marine origin and containing much red materials like those of central Texas and Kansas, are also found through New Mexico, western Colorado, and Wyoming.

In the states farther west, including Arizona, Utah, Idaho, Nevada, and California, there are both marine and non-marine formations of Permian age. Four formations—*Supai* red sandstone and shale, *Hermit*

red shale, *Coconino* gray sandstone, and *Kaibab* white limestone (at the top)—constitute the upper 2000 feet of the picturesque walls of the Grand Canyon of Arizona, but the Upper Permian is missing. The Kaibab is of marine origin, but the others are largely or wholly non-marine.

Marine strata, thousands of feet thick, are known in Alaska, particularly in the Copper River region.

In the Gulf of St. Lawrence region the Permian consists mostly of "Red Beds," including conglomerates, sandstones, and shales.

The Permian Roxbury conglomerate formation of eastern Massachusetts contains glacial materials.

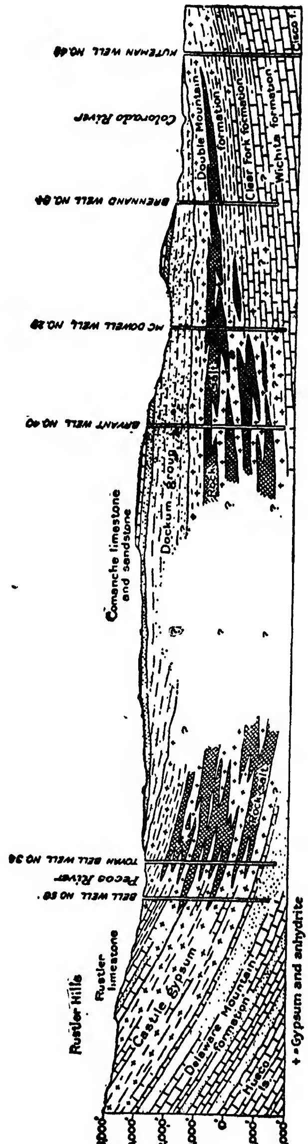


FIG. 104. East-West structure section in western Texas showing the stratigraphic relations of the great salt beds of Permian age. Length of section, 200 miles. Vertical scale, greatly exaggerated. The Permian formations lie between the Hueco (Pennsylvanian?) and the Dockum (Triassic). (After W. H. Hoots, U. S. Geological Survey.)

Structure of the Permian Strata. The Permian strata in the three largest areas, and near by smaller areas, in the southwestern United States, and the Permian of the northern Appalachian region, have been little deformed by either folding or faulting. A fine example of moderate deformation is the broad, very gentle synclinal structure of the great Kansas-Texas area. In most of the other numerous areas of North America, the Permian strata have been more or less folded or faulted, or both.

Thickness of the Permian. In Pennsylvania and Ohio the Dunkard series (Lower Permian only) shows a thickness of about 1000 feet. A thickness of 2000 feet for the whole system is reported from Kansas; 5000 to 14,000 feet in Texas; 3800 feet in Utah; 2000 feet in the Grand Canyon; 6000 feet in Alaska; and 9000 feet in the Gulf of St. Lawrence region.

Igneous and Metamorphic Rocks. Plutonic igneous rocks (mainly granites) of Permian, and possibly somewhat earlier, age occur in numerous large and small bodies in the Piedmont Plateau and so-called Older Appalachians, especially in their southern portions, and also in New England, New Brunswick, Nova Scotia, and Newfoundland (Fig. 162).

Diorites, probably of Permian age, occur in the Sierra Nevada.

Volcanic rocks occur in the Permian system in parts of northern California, western Nevada, western Idaho, and southern Alaska.

Permian strata in the western mountains are in places moderately metamorphosed.

Physical History

Early in Permian time an interior sea spread over much of Nebraska, Kansas, western Oklahoma, central and western Texas, New Mexico, and eastern Colorado and Arizona. This sea seems to have been connected with the Gulf of Mexico through eastern Mexico. At the same time northern California and much of Alaska were submerged. The Early Permian strata (including coal) in the northern Appalachian district clearly prove a continuation of the Coal Measures conditions, that is, large fresh-water swamps or basins and prolific plant growth.

By Middle Permian time the western sea became much enlarged and connected with the Pacific Ocean through northern California and through western Canada, at the same time covering all (or nearly all) of Alaska. This was the greatest Permian sea. Figure 105 shows the sea and land relations of that time.

Rising out of the Middle Permian southwestern sea, a bold range, called the Ancestral Rockies, extended from southeastern Wyoming into eastern New Mexico. A more or less cutoff arm of the sea or basin lay just east of this range during much of Middle Permian time. According to R. A. Jones, a great coral reef, now clearly traceable in fossil form across westernmost Texas and southeastern New Mexico, existed as a barrier separating this lagoonal basin from the sea on the

west. In this basin, lying in an arid region, conditions were favorable for the deposition of the so-called "Red Beds" and associated great beds of salt and gypsum.

In the Gulf of St. Lawrence region, Permian strata are also chiefly of continental origin, suggesting conditions of deposition similar to those in Texas and Kansas, except that salt and gypsum are practically absent.

FIG. 105. Generalized paleogeographic map showing sea and land areas in North America during Middle Permian time. This was the greatest Permian sea. White areas, land; ruled areas, sea. Cross-ruled area, mainly non-marine. A, Ancestral Rockies. Small circles show volcanoes on the Pacific Coast. Principal data (modified) from maps by C. Schuchert and R. Kirkham.

A glacial deposit of Permian age in eastern Massachusetts shows that conditions were favorable for at least local glaciation there. Permian deposits of more doubtful glacial origin have been reported from Prince Edward Island (in Gulf of St. Lawrence) and from Alaska.

Middle Permian volcanoes were active in northwestern California, western Nevada, western Idaho, and southern Alaska.

In Late Permian time the great western sea almost completely vanished, leaving only western Texas, southern New Mexico, and eastern Mexico submerged. This was the last remnant of the wonderful succession of the numerous North American Paleozoic epeiric seas. Late Permian volcanoes were active in northern California and southern Alaska.

At the close of the Permian the sea completely disappeared from the continent.

Close of the Permian (Appalachian Revolution). The Paleozoic era was brought to a close by one of the most profound physical disturbances in the history of North America. It has been called the Appalachian Revolution because at that time the Appalachian Mountain Range was born out of the sea by upheaval and folding of the strata. Perhaps it would be better to say that the revolution reached its climax at about the close of the Paleozoic because breaks in the stratigraphic record prove that the orogeny began as early as the Pennsylvanian, and slowly increased to the close of the era. Since Permian strata are involved in the folding along the western side of the Appalachians, we know that much of the disturbance must have occurred after the deposition of those strata.

All through the vast time (many millions of years) of the Paleozoic era, a great land-mass (Appalachia) existed along what is now the eastern coast of the United States. Its western boundary was, most of the time, just east of the present Appalachians, while it must have extended eastward at least as far as the border of the continental shelf. Concerning the altitude and the character of the topography of Appalachia we know almost nothing, but we do know that it consisted of rock of pre-Cambrian age. The enormous amount of sediment derived from it shows that Appalachia was high enough during nearly all of its history to undergo vigorous erosion. Although oscillations of level more than likely affected the land-mass, and its western shore line was quite certainly shifted at various times, nevertheless it persisted as a great land area with approximately the same position during all of its long history. Its general position is well shown on the various Paleozoic paleogeographic maps.

Barring certain minor oscillations of level, all of the region just west of Appalachia was occupied by sea water during much of the Paleozoic

era, and sediments derived from the erosion of Appalachia were laid down layer upon layer upon that sea bottom. The coarsest and greatest thickness of sediments deposited nearest the land, that is, along what we might call the marginal sea bottom. At the same time, finer sediments and limestones in thinner sheets were being deposited over much of the Mississippi Valley region. By actual measurement, in the present Appalachians, we know that the maximum thickness of these sediments

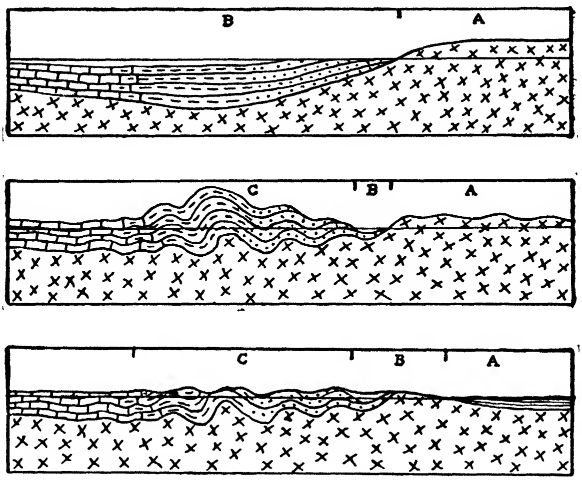


FIG. 106. Highly generalized structure sections across the Appalachian region and adjoining districts to illustrate certain important features in the history of the region. Upper figure: *A,* Appalachia; *B,* marginal sea-bottom (Appalachian geosyncline) mostly filled with sediments derived from Appalachia during Paleozoic time. Middle figure: The same region with the strata folded into mountains as they would have appeared, if unaffected by erosion, toward the close of the Paleozoic era. *A,* Appalachia; *B,* Triassic basin or downwarp; *C,* Appalachian Mountains. Lower figure: The same region as it now appears after much erosion, the submergence of Appalachia, and the deposition of the Coastal Plain beds. *A,* Coastal Plain; *B,* Piedmont Plateau; *C,* Appalachian Mountains.

was at least 25,000 feet. Now, since these are all of comparatively shallow water origin, as proved by the coarseness of sediments, ripple marks, fossil coral reefs, etc., we are forced to conclude that this marginal sea bottom gradually sank during the process of sedimentation, thus producing what is called a great geosynclinal trough. Perhaps the very weight of accumulating sediments caused this sinking. Finally, toward the close of the Paleozoic era, sinking of the marginal sea bottom and deposition of sediments ceased, and a tremendous force

of lateral compression was brought to bear, causing the strata to become highly folded and more or less faulted. Thus arose the great Appalachian Mountain range which, in its prime, was doubtless much loftier than it is today (see Fig. 106).

FIG. 107. Structure section through a portion of the Appalachian Mountains of western Virginia showing the typical deformation of Paleozoic strata. Length of section, 12 miles. *Chk* and *Cn* = Cambrian; *Csk* = Cambro-Ordovician; *Sc*, *Smc*, *Ssv*, *Sb* = Ordovician; *Sr* = Silurian; *SDg* = Siluro-Devonian; *Dk* = Devonian; and *Cgr*, *Cbf*, *Cy*, *Chn*, *Cx*, *Cwl*, *Cr* = Mississippian and Pennsylvanian. (After Campbell, U. S. Geological Survey, Folio 44.)

This tremendous deformation took place very slowly, though during a short time as compared with the length of the Paleozoic era. As soon as the folds appeared well above sea-level, irregularities began to be carved out by the work of erosion so that even from early youth the mountains presented a rugged surface. Mountains now in process of growth, like the Coast Ranges of California, show such ruggedness. The great thrust faults, especially of the southern and central Appalachians, where certain blocks of the earth's outer shell have been pushed for miles to the northwest over others, were not produced by single movements, but rather by many repeated movements along single fault surfaces. Some of these faults are hundreds of miles long.

Important orogenic movements through New England and into the Gulf of St. Lawrence region took place at the same time. Great thrust faulting occurred in western New England. Accordingly, the whole eastern border region of the continent, for a distance of 2000 miles, was profoundly affected by mountain-making disturbances.

The Appalachian Revolution was accompanied by tremendous intrusions of granite magma throughout New England, New Brunswick, and Newfoundland, and to the east of the Appalachian Mountains proper, particularly in the Piedmont Plateau and the so-called "Older Appalachians." The granite is now widely exposed in these regions. An important factor contributing to the present-day height and ruggedness of northern New England and of the southeastern

"Older Appalachian" region is the outcropping of so much of this resistant granite. The two regions last mentioned are the highest and most rugged in eastern North America, the highest peak of all being Mt. Mitchell in North Carolina with an altitude of 6684 feet.

FIG. 108. Nearly horizontal Ordovician strata (*O*) separated by an unconformity (*U*) from nearly vertical Silurian strata (*S*). The originally horizontal Ordovician strata were turned on end at the time of the Late Ordovician (Taconic) Revolution, and, after an interval of erosion followed by submergence under the sea, the Silurian strata were laid down horizontally upon them. At the time of the Appalachian Revolution the Silurian strata were turned on end while at the same time the Ordovician strata were shifted back to a nearly horizontal position. These rocks and their structures, once deeply buried, have been brought to light by post-Paleozoic erosion near Port Clinton, Pennsylvania. (Photo by N. H. Darton, U. S. Geological Survey.)

It should be stated that the original Appalachian Mountains were greatly worn down in post-Paleozoic time and then rejuvenated to form the present-day mountains.

Other important geologic changes in addition to the above were (1) the warping of the surface of Appalachia as we shall show in our discussion of the Triassic period; (2) the uplift of the Mississippi Basin, with little deformation of the strata, east of the Great Plains never again to become submerged to the present time except along the Gulf Coast; (3) the elevation and erosion of many of the Permian areas west of the Rocky Mountains in the United States, which thus accounts for a rather widespread unconformity between the Permian and Triassic in those areas; (4) deformation of the rocks, accompanied by metamorphism of strata and intrusion of plutonic bodies (mainly diorites), in the Sierra Nevada region; and (5) probably continued deformation, especially thrust faulting, in the Ouachita Mountains region.

All of North America was land at the end of Permian time.

Climate

During Permian time there was a remarkable combination of climatic conditions, including extensive glaciation especially in the southern hemisphere (described beyond), widespread aridity in parts of North America and Europe, and conditions favorable for prolific growth of coal-forming plants in various parts of the world, all in a single period. Thus the climate of the Permian presented a striking contrast to the mild and rather uniform climate of the immediately preceding period. The concentration of the extensive glaciation over low-latitude, instead of high-latitude, regions is difficult to account for.

These perplexing problems may be in part explained as follows. The profound mountain-making disturbances, resulting in so many great and small uplifts in so many large parts of the world, caused (1) general disappearance of seas from continents and great interference with the free play of ocean currents, thus much reducing the temperature equalizing influence of the seas; (2) low temperatures over extensive regions newly raised to high altitudes, even in low latitudes; and (3) heavy precipitation on the windward sides of new mountain ranges which rose across the paths of prevailing winds, and low precipitation on the opposite sides.

Economic Products

Coal beds of considerable economic importance occur in the Permian of the northern Appalachian belt, France, Germany, Bohemia, Australia, Transvaal, and Brazil.

Most of the oil and gas from important fields in western Texas come from Permian strata.

Salt is obtained from the Permian strata of Kansas, Oklahoma, and central Europe.

Gypsum deposits, which are so widespread in rocks of Permian age, are quarried in many states as Iowa, Kansas, Oklahoma, Texas, New Mexico, South Dakota, and Colorado.

The recently discovered potash deposits in the Permian of Texas bear promise of great commercial value.

There are also important gypsum and potash deposits in Europe.

Foreign Permian

Europe. The Permian of Europe also shows two rather distinct phases—marine and non-marine—but the system in central and western Europe is usually separated from the underlying Upper Carboniferous (Pennsylvanian) by unconformity. Early in the Permian a great salt lake (or series of lakes), sometimes with local fresh-water conditions, extended over western to central Europe from Ireland to central Germany. "Red Beds," consisting of sandstones, shales, marls, salt, and gypsum, together with some coal beds, were formed in these inland water bodies. Fossils prove that marine waters sometimes spread over at least portions of this inland basin. Glacial deposits have recently been discovered toward the base of the Permian in Germany. Another feature of special interest is the large amount of igneous rock in the form of lava flows, dikes, and tuffs in the Lower Permian, particularly in the British Isles, Germany, France, and the Alps.

The Late Pennsylvanian orogeny, which affected parts of central and western Europe, continued with abating force through Permian time.

Both Lower and Upper Permian marine strata occur in parts of southern Europe.

About the beginning of the Late Permian, marine waters appear to have prevailed over the enclosed basin areas of central and western Europe, but soon again those waters withdrew to restore salt lake conditions. Neither coal nor igneous rock occurs in the Upper Permian, but the greatest salt beds in the world were deposited in northern Germany during late Permian time. Some layers of magnesium and potassium salts were deposited with the common salt, one well having penetrated the deposit near Berlin to a depth of 4000 feet without reaching the bottom.

In Russia, the type region for the Permian, rocks of this age underlie much of the country and appear at the surface over a wide area in the eastern part, just west of the Ural Mountains. These rocks are usually conformable upon the Upper Carboniferous (Pennsylvania). Nonmarine deposits, including "Red Beds" with salt and gypsum, are common, though at some horizons true marine strata prove incursions of the sea.

Other Continents. In many other parts of the world Permian rocks are extensively developed, particularly in northern Asia, China,

FIG. 109. A rock surface grooved, striated, and polished by a Permian glacier. The glaciated surface, long buried under later sediments, has recently been uncovered by erosion of the once overlying material. Nooitgedacht, South Africa. (Photo by R. T. Chamberlin.)

Persia, northern India (including the Himalayas), South Africa, Australia, Tasmania, New Zealand, Argentina, and Brazil. Continental deposits are common. A most remarkable feature is the widespread occurrence of thick (sometimes from 1000 to 2000 feet) glacial deposits in the Permian system in low-latitude countries such as India, South Africa, southern Brazil, and Australia. Furthermore, the plain inference from the close association of certain of these glacial deposits with marine strata is that *glaciers near the equator came down near or actually to sea level.*

According to the work of Du Toit, there are two remarkable facts about the Permian glacial deposits: (1) "that the movement of the ice was southerly, pole-ward and away from the equator, the opposite to what would be expected", and (2) "that the ice in Natal invaded the land from what is now the sea to the northeast." There was a truly great Ice Age in the southern hemisphere.

Mention should also be made of the fact that coal beds of Permian age occur in various parts of the world, though they are much less important than the Pennsylvanian coal deposits.

CHAPTER XVII

LATER PALEOZOIC LIFE

PLANTS

Later Paleozoic Thallophytes. Of the thallophytes, both sea weeds and diatoms are known in fossil form from Later Paleozoic strata. Certain forms regarded as treelike *seaweeds* were remarkable for their size, having attained a diameter of two or three feet. *Diatoms* are unicellular, aquatic plants of microscopic size which secrete shells of silica, and some of Devonian age are known. In some of the later periods these tiny plants were of considerable importance.

Devonian and Mississippian Plants. Spores and spore-cases of certain aquatic plants (rhizocarps), probably related to very simple *pteridophytes,* are very abundant in Devonian shales, especially those of Marcellus and Hamilton ages. According to Dawson they are "dispersed in countless millions of tons through the Devonian shales," and by their decomposition much oil has been produced.

Our knowledge of land plants prior to the Devonian is very scant as we have seen, but the records are sufficient to make it certain that the Devonian lands were covered with a rich and diversified vegetation, often even with luxuriant forests. The forests were, however, far different in appearance from those of the present because the trees were all of very simple or low organization types. Figs. 110 and 111 represent two types of these very primitive trees. Thus they were largely represented by all the main subdivisions of the seedless plants and primitive types of low-order gymnosperms. Because these important and remarkable land plants reached their climax of development in the Pennsylvanian (great coal period), it will serve our purpose best to discuss these plants in connection with the flora of that period.

During Mississippian time there were comparatively few important evolutionary advances in the plant world.

Pennsylvanian Plants. *General statement.* The plant life of Pennsylvanian time was, however, very prolific and the records for this period are far more abundant than for any other Paleozoic period, one

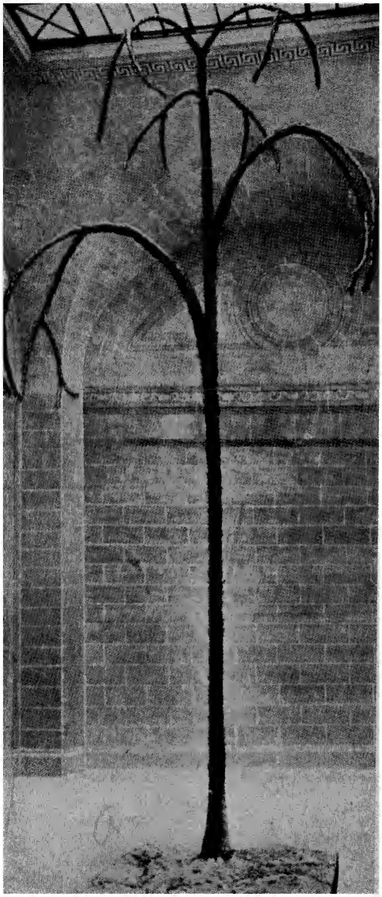


FIG. 110. A restoration of one of the oldest trees of the earth. It is a primitive lepidophyte (*Archeosigillaria primeva*) reconstructed from a specimen found in the Devonian strata of New York. (Courtesy of the New York State Museum.)

reason for this unusually full record doubtless being the very favorable conditions for preservation of the flora of the time. Several thousand species of now extinct plants are known from the Pennsylvanian alone. It must be remembered that most of the important classes of Pennsyl-

vanian plants existed as early as in the Devonian, but that the earlier records are much more scant. The known Pennsylvanian flora consists very largely of seedless plants together with some primitive, low-order gymnosperms. From the negative standpoint, a most significant feature was the complete absence of the true flowering plants (angio-

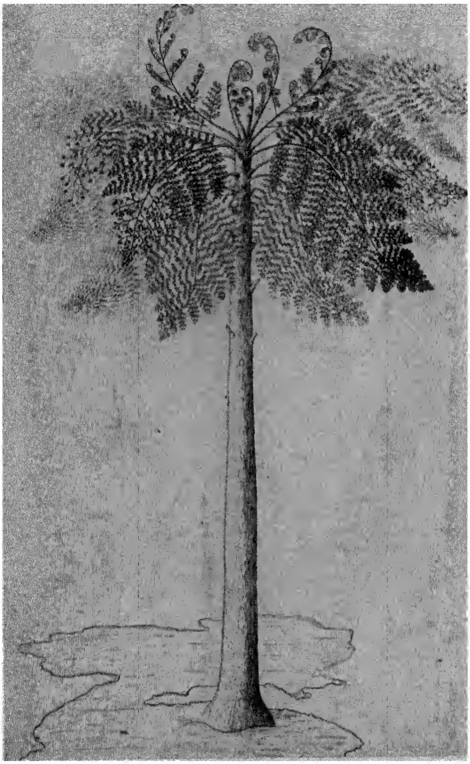


FIG. 111. A restoration of a primitive treelike seed fern (*Eospermatopteris*) from the Devonian strata of New York. (Courtesy of the New York State Museum.)

sperms) which are today the most common and the most advanced of all plants.

Pteridophytes. *Filicales* (ferns) were very common and diversified, both as treelike forms and as small, herbaceous forms. Both forms were very similar in appearance to those now living in tropical and temperate climates (Fig. 112). They ranged from Silurian time to the present. Thousands of species are now living.

Arthrophytes ("horsetail rushes") were common in the Pennsylvanian forests. These plants had long, slender, segmented stems which were either hollow or filled with a large, soft pith (Fig. 113). The leaves, which were arranged in whorls around the stems at the joints, were of variable shapes and sizes, usually either needle-like, scale like, or strap like. The outside of the stem had a sort of finely fluted structure but without scars and not continuous as in the sigillarians. They reached heights of 60 to 90 feet and diameters of 1 or 2 feet. Arthrophytes are today chiefly represented by only a few species of rushlike

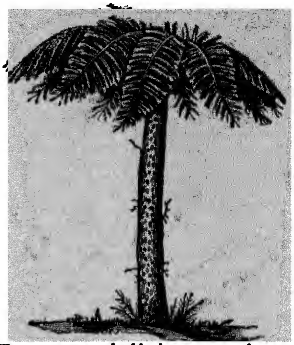


FIG. 112. A living tree fern. (From Le Conte's "Geology," permission of D. Appleton and Company.)

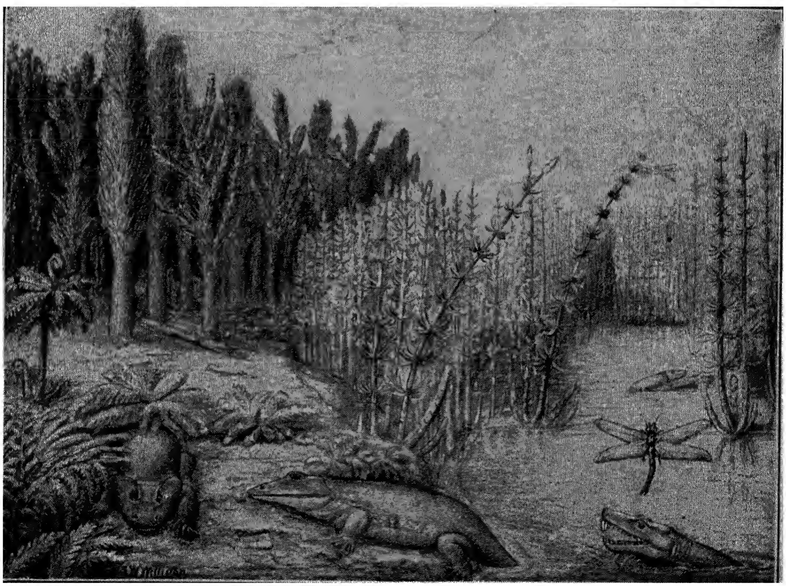
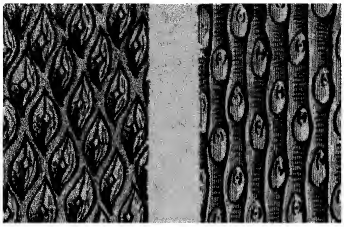


FIG. 113. A Permo-Carboniferous landscape, showing some of the most conspicuous plants of the great Coal Age. Lepidodendrons (with branches) and sigillarians (without branches) in the left background; arthrophytes (segmented) on the right; seed ferns in the left foreground; two amphibians (*Eryops*) on the land; a primitive reptile (*Limnoscelis*) in the water; and a great insect (dragon fly) in the air. (From a drawing by Prof. S. W. Williston.)

forms not over a few feet high, though in South America some very slender forms grow to heights of 30 or 40 feet.



a *b*

FIG. 114. Lepidodendron bark (*a*) and sigillarian bark (*b*), showing arrangement of leaf-scars.

Lepidophytes (giant "club mosses") were the largest, most abundant, and conspicuous of the forest trees, and they appear to have culminated during this same period. In marked contrast to such a high position their descendants of today are represented only by a few, small, delicate, trailing so-called "club mosses" and "ground pines" in our forests. Two of the most prominent of the Pennsylvanian lepidophytes were the

FIG. 115. A fossil lepidophyte (sigillarian) stump in the Pennsylvanian strata of Nova Scotia standing in the position where the tree grew. (Courtesy of the Geological Survey of Canada.)

lepidodendrons and the *sigillarians.* The *lepidodendrons* ("scale trees") had leaf-scars or scales arranged spirally around the trunks of the trees (Fig. 114a). They generally attained a height of 50 to 100 feet and a diameter of 2 to 4 feet. The tall trunks were slender and they branched dichotomously (by twos) only at a considerable height. Long, stiff, needle-shaped leaves were thickly set on the branches. The dropping of the leaves from the older (trunk) portions caused the leaf-scars or

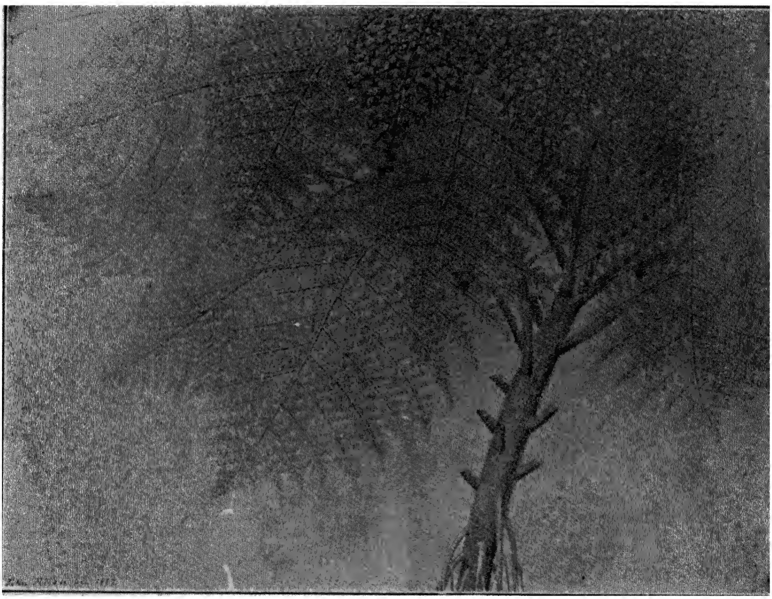


FIG. 116. A pteridosperm or seed fern. Restored by D. H. Scott and J. Allen. (From Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

scales above mentioned. Inside of the outer bark, the stem consisted of pithy or loose cellular tissue. Over 100 species of the lepidodendron are known. The *sigillarians* ("seal trees") are so called because of seal-like markings (Fig. 114b) which were arranged vertically on the tree trunk. They were even larger than the lepidodendrons, having attained a height of 100 feet or more and a diameter of 5 or 6 feet. The trunk seldom branched and it ended with a rounded tip. In other respects these trees were much like the lepidodendrons. A very primitive lepidophyte is shown by Figure 110, and two typical Pennsylvanian forms

in Figure 113. Lepidophytes ranged from the Devonian to the present, culminating in the Pennsylvanian.

Gymnosperms. Pteridosperms ("seed ferns"), which were common in the Pennsylvanian, comprised a remarkable group of plants recently regarded as transitional between the seedless and seed plants. They possessed seeds but not flowers and showed many features which seem to make them the connecting link between the ferns and the cycads. The seeds were arranged on the leaves. There is considerable difference of opinion concerning the relations and affinities of this remarkable group of plants, now long extinct.

Fig. 117. Cordaites restored. (From Schuchert's "Historical Geology," courtesy of John Wiley and Sons.)

Figure 2 shows a well-preserved (carbonized) frond of a Pennsylvanian seed fern on a piece of shale, and Figure 116 shows a restoration of a considerable part of a typical plant. A very primitive seed fern (restored) is illustrated by Figure 111. Seed ferns ranged from Devonian to Triassic.

Cordaites were common representatives of low-order gymnosperms. They were comparatively slender trees which attained a diameter of 2 or 3 feet and a height of 90 feet or more (see Fig. 117). The branches, which were given off only toward the top of the trunk, were supplied with numerous, long, very simple, parallel-veined, strap-shaped leaves notable for great size, sometimes 5 or 6 feet long and 5 or 6 inches wide. The trunks were covered with thick bark, while inside there was much pith. Many specimens have been well preserved. They were important contributors to the formation of some coal beds. They possessed

certain features or structures of the seed ferns, conifers, cycads, and ginkgos in addition to their own characteristics. Cordaites thus afford a fine illustration of a generalized type of plant, that is to say one which combined the characters of several distinct (some later) forms. Cordaites ranged from the Devonian to the Triassic.

Higher types of gymnosperms such as cycads [1] and conifers are not certainly known to have existed during Pennsylvanian time.

Permian Plants. In Permian time the most important advances in the plant world occurred among the *gymnosperms*. Thus *cycads* and *conifers*, with their primitive flowers, first appeared and gave vegetation a decided Mesozoic aspect. Cycads evolved from seed ferns, and conifers from the cordaites. *Ginkgo* ("maidenhair") trees evolved from cordaites or an allied plant during the Permian. The so-called "tongue ferns" (e.g. *Glossopteris*) were widespread in the southern hemisphere. They had primitive tongue-shaped leaves and they bore seeds, hence they were not ferns but related to the cycads.

INVERTEBRATES

Protozoans. These were represented by both *foraminifers* (Fig. 360) and *radiolarians*, and they were more or less common in Later Paleozoic time.

Sponges. These were abundant in Later Paleozoic time. They have been found in a remarkable state of preservation in the Devonian of New York. Certain of these, known as "glass sponges," had siliceous skeletal frameworks of beautifully intricate designs (Fig. 128).

Coelenterates. *Corals* increased in numbers, species, and size in the Devonian. They must have grown in profusion, especially in the clear Onondaga sea, as proved by the many great fossil coral reefs. From near Louisville, Kentucky, alone more than 200 species are known, and these are only a fraction of all described Devonian species. They were almost all of the cup and honeycomb types, the chain corals having become rare and extinct in the early Devonian. The solitary cup corals probably reached their culmination in size, some of them being 12 to 18 inches long and several inches in diameter. The cup and honeycomb corals, representing the ancient Tetracoralla, continued through the rest of Paleozoic time. In the Permian, however, corals showed an im-

[1] In this book the term "cycad" is used in a broad sense to include the ancient cycadeoids.

portant change in their evolution by the first appearance of the more modern Hexacoralla, or forms whose septa or dividing walls were six in number or multiples of six.

The *graptolites* continued into the Mississippian period when they became extinct.

Echinoderms. The very primitive stalked echinoderms, called *cystoids,* were rare in Later Paleozoic time, becoming extinct in the Permian.

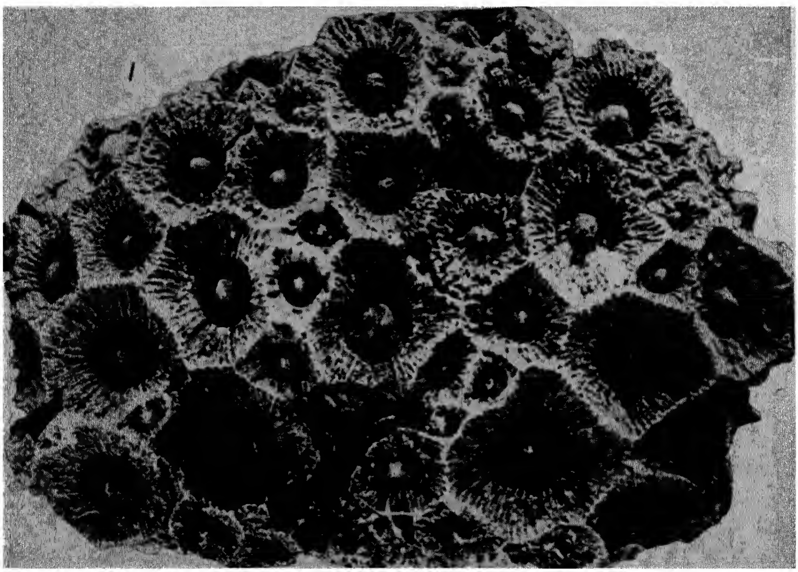


FIG. 118. Mississippian cup corals, *Lithostrotion canadense,* forming a compact mass or colony. (After Ulrich, U. S. Geological Survey, Folio 95.)

Blastoids, which, during several preceding periods, assumed a minor rôle, showed a wonderful development in the Mississippian when they appear to have reached their culmination both as regards numbers of individuals and diversity of forms. Fig. 119 shows one of the most common types, known as Pentremites, which largely constitutes beds of limestone in some places. At certain localities even the most delicate of the hard parts of the organisms are nearly perfectly preserved. It is a remarkable fact that this class of animals, which attained such prominence during this period, also became nearly extinct by the close of the same period.

Crinoids also culminated in the Mississippian. Hundreds of species are known, and some localities such as Crawfordsville, Indiana, and Burlington, Iowa, are well known for the remarkable preservation of vast numbers of these beautiful forms (fossil "sea lilies"). "The crinoid remains occur in such multitudes that in many places the limestones are principally composed of them; in such places they must have covered the sea-bottom like miniature forests" (W. B. Scott). It is noteworthy that all of this wealth of forms belonged to a single subclass or order of crinoids, not one of which is known to have lived on into the Mesozoic.

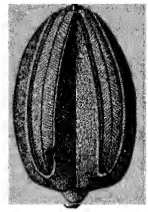


FIG. 119. A Mississippian blastoid head, *Pentremites elongatus.* (After Shumard.)

The blastoids became extinct in Pennsylvanian time, and the crinoids declined greatly in Pennsylvanian and Permian times.

Both *echinoids* (sea urchins) and *asterozoans* (true starfishes) were more or less common during Later Paleozoic time, but neither showed any great evolutionary change.

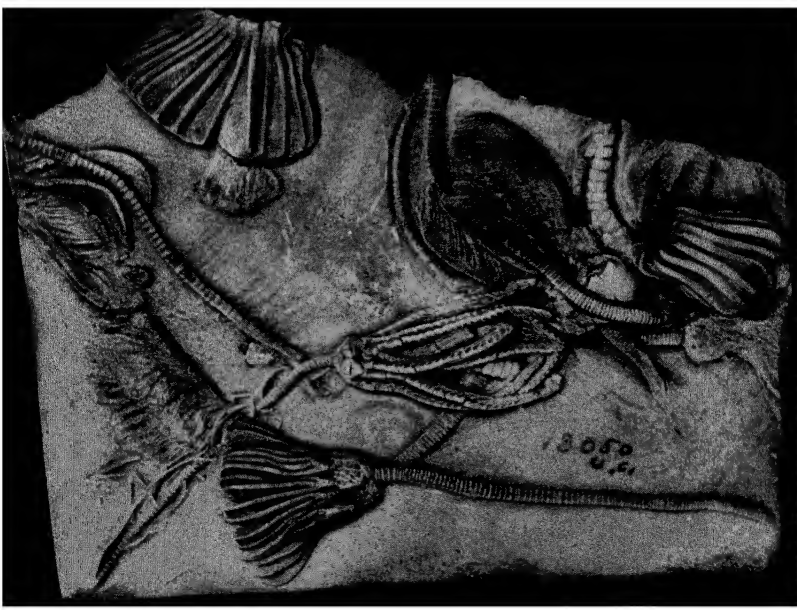


FIG. 120. Mississippian crinoids, *Graphiocrinus longicirrifer* and *Rhodocrinus Kirbyi,* on a slab of limestone. Considerably reduced. From Kinderhook formation, Le Grand, Iowa. (Courtesy of the University of Chicago.)

Molluscoids. *Bryozoans* ranged through all of Later Palezoic time. They were very abundant in the Mississippian, and in some cases the calcareous skeletons of the colonies contributed much material to the building of limestone. For the first time (Mississippian) the delicate, mosslike, colony supports were partly replaced by thicker and heavier ones.

Brachiopods reached their culmination, in regard to number of species and abundance, in the Devonian period (Fig. 122). They were still

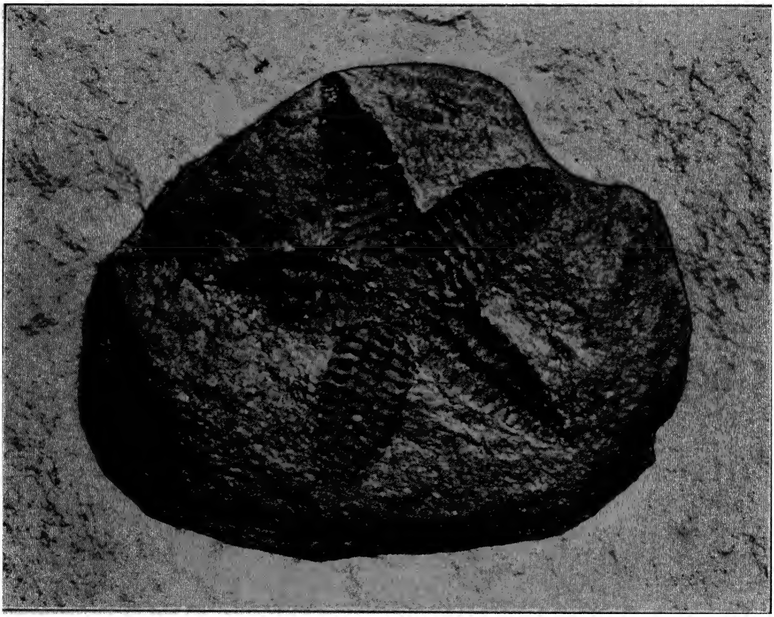


FIG. 121. A Devonian asterozoan, *Paleaster eucharis,* on a pelecypod shell. (After Clarke, *N. Y. State Mus. Bul. 158.*)

among the most numerous animals. Most of them still had straight hinge lines. Many *spirifers,* particularly the wide ("butterfly") types (Fig. 122a), were common and characteristic. *Pentamerus* was also represented by many species.

Brachiopods declined in the Mississippian, though they were by no means uncommon. Certain important earlier Paleozoic genera (e.g. *Pentamerus*) were entirely gone. The important genus *Spirifer* greatly diminished in numbers and size of individuals. Perhaps the most important Mississippian genus was *Productus* with many species and some

of the largest known individual brachiopods. Straight-hinge line types still prevailed.

A very fine illustration of the production of a dwarfed fauna due to unfavorable environmental influences is afforded by the diminutive

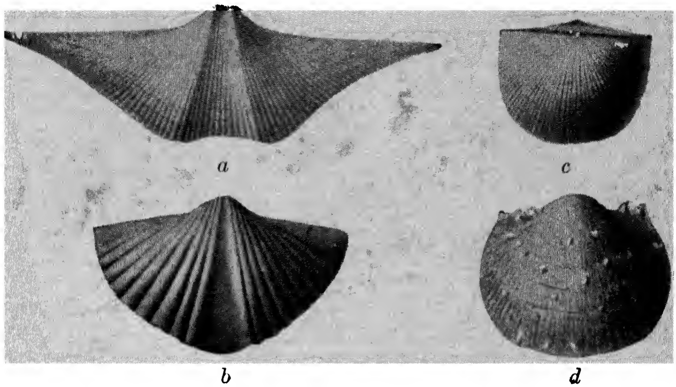


FIG. 122. Devonian brachiopods: *a, Spirifer disjunctus; b, Spirifer intermedius; c, Stropheodonta demissa; d, Productus Hallanus.* (All from Md. Geol. Survey.)

brachiopods and associated shells of the Salem limestone of Indiana. Since the species of these dwarfed forms are the same as those which grew to normal size elsewhere, it is evident that they must have lived in an unfavorable environment.

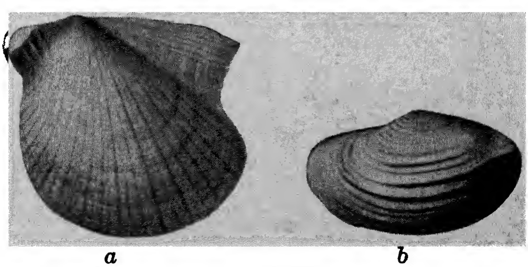


FIG. 123. Devonian pelecypods: *a, Actinopteriate textilis; b, Grammysia arcuata.* (From Md. Geol. Survey.)

A noteworthy fact about Pennsylvanian brachiopods was the almost world-wide distribution of some of the species, indicating either actual land bridges or at least shallow-water areas connecting all the continents.

In the Permian brachiopods continued to be common with straight-hinged types, so abundant through the Paleozoic era, prevalent for the last time.

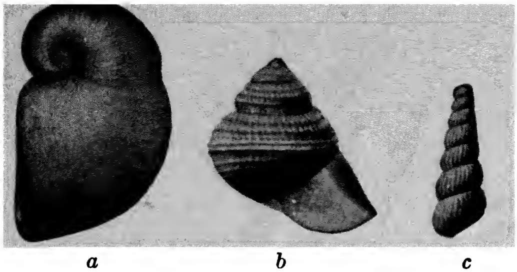


FIG. 124. Devonian gastropods: *a, Platyceras gebhardi; b, Pleuromaria capillaria; c, Loxonema hamiltoniæ.* (From Md. Geol. Survey)

Mollusks. *Pelecypods* generally increased in numbers of species and individuals in Later Paleozoic time, becoming more numerous than the declining brachiopods.

Gastropods continued to be common, with various species changes, in Later Paleozoic time. Several species of the earliest known land snails have been found in Pennsylvanian strata.

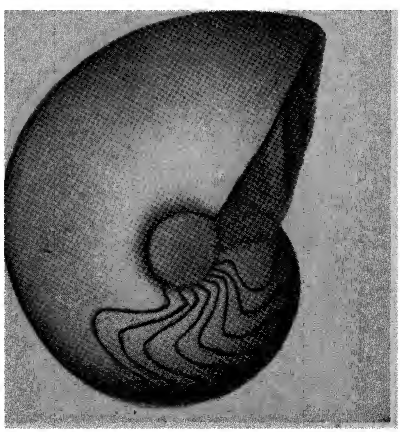


FIG. 125. A Devonian ammonoid, *Manticoceras sinuosum.* (After Hall.)

Chambered *cephalopods* showed a significant evolutionary change in the Devonian with the introduction of the *ammonoids* (Fig. 125) in which the septa or partition junctions were angular or irregular instead

of simple or straight as in all previous forms (nautiloids). As we shall see, this irregularity of partition structure gradually evolved into more and more complex forms, reaching a maximum in the Mesozoic era. (See table on page 287.) Examples of Later Paleozoic ammonoids are shown by Figures 125, 126, and 127.

Many nautiloid types still persisted in the Later Paleozoic, but these simpler forms (straight and slightly curved) were greatly reduced in prominence. The coiled nautiloids probably reached their climax of development, in regard to both numbers and diversity of forms, in the Mississippian.

In the Permian some Earlier Paleozoic types of nautiloids (e.g. Orthoceras) still persisted, and certain species of the modern genus

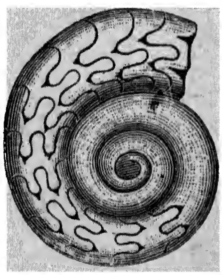


FIG. 126. A Pennsylvanian ammonoid (*Goniatites lyoni.* After Meek.)

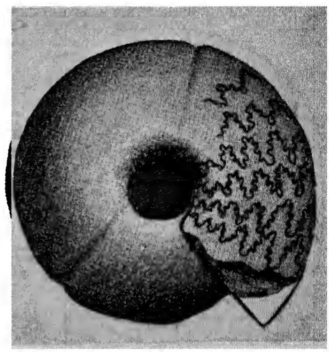


FIG. 127. A Permian ammonoid, *Waagenoceras cumminsi* (White) showing highly folded suture (partition) lines.

Nautilus were added. Permian ammonoids, because of their rather complex partition structures, were really more suggestive of Mesozoic ammonites than of Paleozoic nautiloids (Fig. 127).

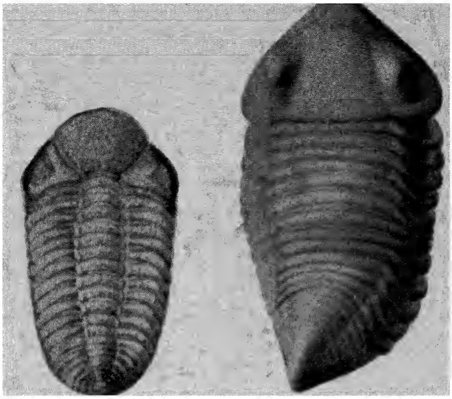
Arthropods. *Trilobites* continued to be important in Devonian time after which they rapidly declined to become extinct in the Permian. Many of the Devonian trilobites showed fantastic body forms and ornamentations.

Eucrustaceans of shrimplike and crayfish-like forms are found in Later Paleozoic rocks.

Eurypterids probably culminated in the Silurian, but Devonian forms were prominent and often remarkedly large, one type having reached

FIG. 128. Restorations of Upper Devonian life of New York. Glass sponges (at left), close-coiled chambered cephalopod (at left middle), straight chambered cephalopod (at right middle), stalked echinoderm or "stone lily" (at right), fishes, asterozoans, and pelecypods. (Courtesy of the New York State Museum.)

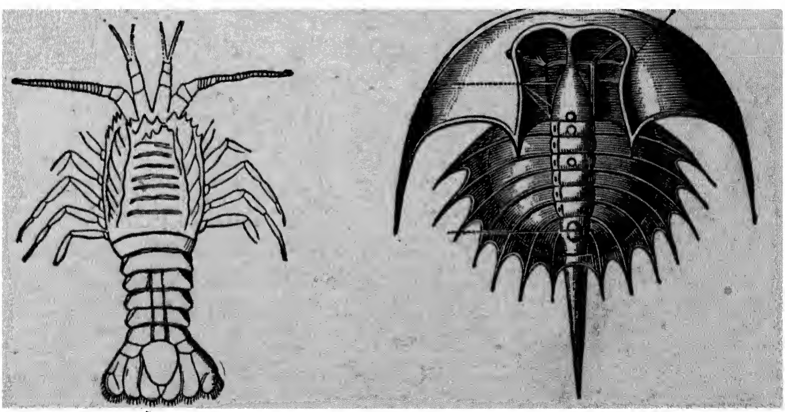
a length of 8 feet. Then they steadily diminished and died out by the end of the Paleozoic era.



a b

FIG. 129. Devonian trilobites: *a, Phacops logani* (Hall); *b, Homalonotus noticus* (Clarke).

Spiders and *myriapods* made their first known appearance in the Devonian. *Scorpions* are also known. It is significant that the last three named were all air-breathers.



a b

FIG. 130. Pennsylvanian arthropods: *a,* a eucrustacean, *Anthrapalæmon gracilis* (Meek and Worthen); *b,* an arachnid related to the modern horseshoe crab, *Euproöps danæ* (Meek and Worthen). (From Le Conte's "Geology," permission of D. Appleton and Company.)

Certain other arachnids, related to the modern horseshoe crabs, have been found in Later Paleozoic rocks.

Insects, including the oldest known fossil forms, occur in Pennsylvanian rocks. Their appearance marked a notable advance in the evolution of invertebrate life because they include the most highly organized

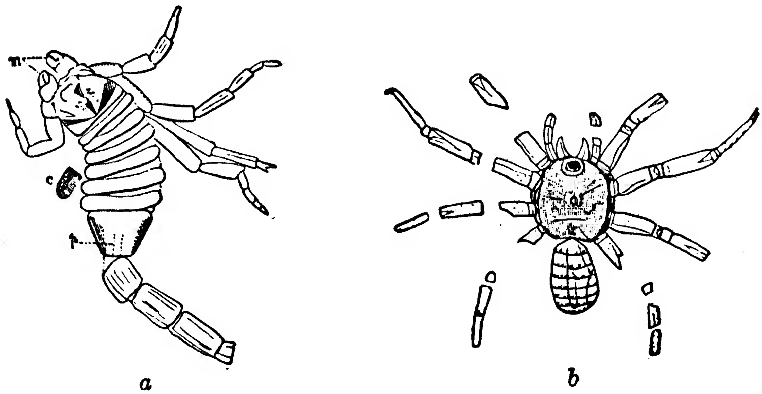


FIG. 131. Pennsylvanian arachnids: *a,* scorpion, *Eoscorpius carbonarius* (Meek and Worthen); *b,* spider, *Anthrolycosa antiqua* (Beecher). (From Le Conte's "Geology," permission of D. Appleton and Company.)

of these creatures. As would be expected in accordance with the abundant and favorable plant environment, the insects showed a notable

FIG. 132. A Pennsylvanian insect, ***Corydaloides scudderi*** (Brongniart). This insect had a spread of wing of 18 inches. (From Le Conte's "Geology," permission of D. Appleton and Company.)

development. Hundreds of species are known from the Pennsylvanian of America alone. Nearly all were of simple types belonging to the orthopters and neuropters, which orders are represented by modern

grasshoppers, cockroaches, caddisflies, etc. Somewhat higher types may possibly have been present, but the highest insects, such as butterflies, bees, ants, etc., are not known to have existed. Two other noteworthy facts regarding Pennsylvanian insects are: (1) Their great size, some having had a spread of wing of from 1 to 2½ feet (Fig. 132); and (2) the existence of three pairs of wings on some species. Probably the most common of all Pennsylvanian insects were the cockroaches, hundreds of species being known. Some specimens are several inches long.

Permian insects were common and much like those of the Pennsylvanian.

VERTEBRATES

Simplest Vertebrates. The primitive, very low-order vertebrates are of unusual significance because they were the progenitors of the great groups of higher vertebrates which gradually became more complex and diversified, and finally culminated in man himself.

"Before mammals, before the birds, the reptiles, the amphibians, came fishes, and paleontologists and zoölogists generally agree that all these vertebrate animals, high and low, can trace their ancestry back to the marine creature who first encased his spinal cord in a hard protective covering which gave his body rigidity with suppleness. . . . There exist to this day living forms which are believed to closely resemble this ancestral vertebrate who lived so many millions of years ago that we hesitate to count them. These are the lowly *lancelets*. . . . The lancelet, generally classed among the fishes, although not a true fish, usually reaches a length of only a couple of inches" (S. F. Hildebrand). The lancelet has no jaws, the mouth being a lengthwise slit; has no true vertebrae, but has a cartilaginous rod through the body; and has no hard parts, limbs, or fins. The modern *lamprey eels* are a step higher in the scale of life. Neither lancelets nor lampreys are known in fossil form, but certain forms zoölogically similar to them have been found in the earlier and middle Paleozoic rocks. Two of these will now be described.

Paleospondylus. This remarkable creature was an exceedingly simple and primitive type of Devonian vertebrate. Its appearance is well shown in Fig. 133. The animal, one or two inches long, possessed a distinct, slender, segmented, cartilaginous vertebral column supplied at one end with a rather symmetrical tail fin structure, and at the other with a head. The head had a circular mouth but no jaws. Its lack

of jaws and paired fins cause it to rank below the true fishes, and it is probably closely related to the lamprey eels.

FIG. 133. A very simple Devonian vertebrate, *Paleospondylus gunni.* (After Dean, restored by Traquair, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

Ostracoderms. These curious and bizarre forms also represent a very simple class of the vertebrates. For a long time they were classed as simple fishes, but recent study has led some to believe that they were

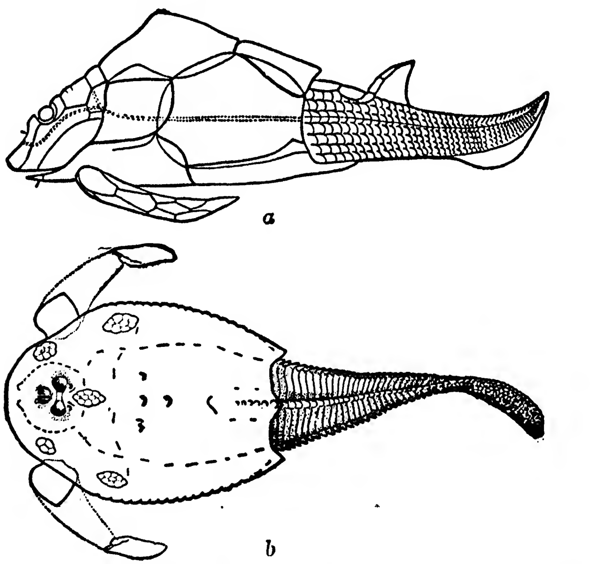


FIG. 134. Devonian ostracoderms: ***a, Pterichthys testudinarius,*** restored (Dean after Woodward); ***b, Trematаspis,*** restored (after Patten).

really transition forms between the highest invertebrates (arthropods) and the fishes which rank very low among the vertebrates.

According to W. K. Gregory, the ostracoderms were ancestral "vertebrates from which were derived, on the one hand, the so-called jawless

cyclostomes, or lampreys and hags, and on the other hand, the jaw-bearing vertebrates, comprising true fishes, amphibians, reptiles, birds, and mammals."

A characteristic feature was the cover or armor of bony plates developed in the skin over the head and fore part of the body, hence the name, which literally means "shell-skin." The rear part of the body was generally covered with scales. Some had vertebrated tail fins and were fishlike in appearance (Fig. 134a). They were rarely if ever more than 6 or 8 inches long. Some had a pair of jointed flappers or swimming paddles extending out from the fore part of the body, but none had true paired fins like the fishes. The vertebral column was of cartilage (gristle). The eyes were close together near the top of the head. They did not possess true jaws in the vertebrate sense of that

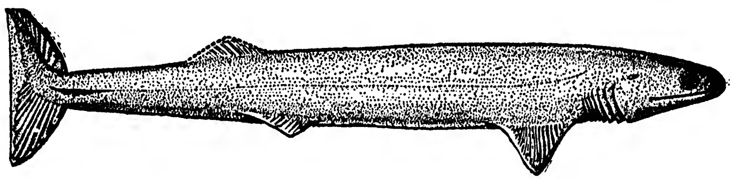


FIG. 135. A Paleozoic (early Mississippian) selachian or shark, *Cladoselache fyleri.* (Restored by Dean.)

term, but rather the simple jawlike portions moved over each other laterally as in many arthropods (e.g. beetles).

Ostracoderms started in the Ordovician, reached the zenith of their development in the Devonian, and, so far as known, they became extinct during the same period.

Fishes. Because of the profusion of fishes, the Devonian is often called the "Age of Fishes." Their abundance, together with their importance as bearing upon the evolution of the vertebrates, requires that considerable attention be devoted to the fishes here. In all of our discussion of the geological history of fishes, the following important groups only will be recognized: (1) *selachians* ("cartilage fishes"), now uncommon, but e.g. sharks; (2) *dipnoans* ("lung fishes"), now rare, but e.g. Ceratodus of Australian rivers; (3) *arthrodirans* (e.g. Fig. 136b), now wholly extinct; (4) *ganoids* ("lustre" fishes), now uncommon, but e.g. gar pike and sturgeon; and (5) *teleosts* ("perfect bone" fishes), now the most abundant of all fishes, e.g. trout, salmon, cod.

Selachians are the simplest of all true fishes, and they comprise the oldest group of living fishes, dating back at least to the Silurian. Their skeletons are wholly cartilaginous, the only hard parts being the teeth and fin spines which are commonly preserved as fossils. The arrangement of separate gill slits in the throat wall is a more eellike than fishlike feature. Simple, paired fins are present, but scales or plates are absent. They were common in the Devonian seas, and also probably in lakes and lagoons. Fig. 135 exhibits a typical Paleozoic species which is very similar to living form.

Mississippian sharks showed an extraordinary development in numbers and species. They were doubtless the most prominent of all fishes

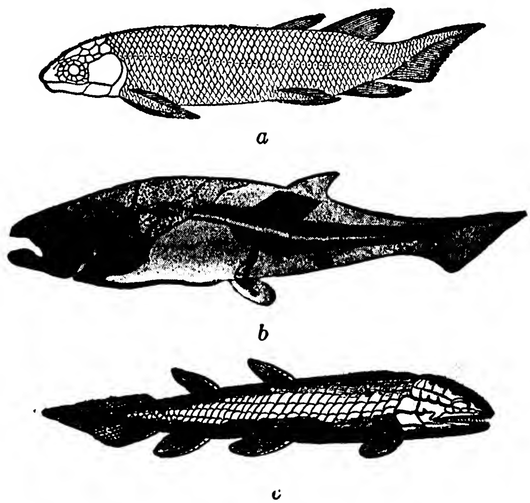


FIG. 136. Devonian fishes: *a*, dipnoan, *Dipterus valenciennesi* (restored by Traquair); *b*, arthrodiran, *Coccosteus decipiens* (restored by Woodward); *c*, ganoid, *Osteolepis* (restored by Nicholson).

of the time, many hundreds of species being known. Teeth and spines are the most numerous fossils. In sharp contrast with most modern forms, many species had the mouths lined or paved with rough platelike teeth probably suitable for grinding such shelled animals as brachiopods, pelecypods, etc. The spines were doubtless provided for defense against more predaceous fishes.

Dipnoans are remarkable in being able to breathe both in water and air, since they have both gills and lung, the air-bladder being more or less used as a lung. They were abundant during Devonian time. Fig. 136a shows a common Devonian species which is remarkably similar to

the modern Ceratodus. Note the paddle-shaped paired fins, almost like legs, and the covering of scales. Their skeletons were cartilaginous. Their limblike fins and peculiar lunglike air sacs were more amphibian-like than fishlike characters and they strongly suggest that the dipnoans may have been the progenitors of the amphibians. Some dipnoans still exist.

Arthrodirans comprise a remarkable group of fishes now wholly extinct. They were common in Devonian time, but declined in the late Paleozoic. Fig. 136b shows an example of a well-known genus (Coccosteus) from the Old Red Sandstone. Note the bony armor covering the fore part of the body, thus suggesting the ostracoderms, though the paired fins and true jaws supplied with teeth place them with the fishes. The spinal cord was of unsegmented cartilage. Other forms closely related to Coccosteus were remarkable for size, some having attained lengths up to 20 or 25 feet. Arthrodirans were probably the most formidable denizens of the Devonian seas.

Ganoids were among the most highly organized and abundant fishes of Devonian and late Paleozoic time. These were characterized by a covering of small lustrous plates or bony scales, usually rhomboid and set together like tile, rather than by overlapping as in typical modern fishes. The skeletons were of cartilage, though in later periods they were more or less ossified as in the few modern representatives. Their internal tooth structure was often labyrinthine (Fig. 137) or much like that of amphibians of later Paleozoic periods. A typical Devonian ganoid is shown in Fig. 136c. The so-called fringe-finned ganoids (crossopterygians, Fig. 139,5) were externally rather similar to the dipnoans, especially as regards the paired, lobate, limblike fins. Their intricate (labyrinthine) tooth structure, character of the skull bones, and limblike fins, suggest strong affinities with the amphibians of the later Paleozoic. The amphibians probably evolved from them.

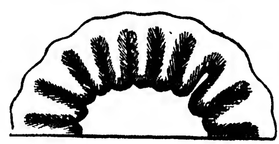


FIG. 137. Structure of a ganoid tooth. (After Agassiz.)

Teleosts, which are the most common and typical modern fishes, were entirely absent from the Devonian. In these the skeletons are completely ossified and the body is nearly always covered with overlapping scales. In marked contrast with the Devonian fishes, teleosts always have non-vertebrated tail fins.

General Observations on Devonian Fishes. (1) All were of simple types. The most typical and highly organized fishes so common today,

did not exist in the Devonian, and even the ganoids were of primitive types.

(2) All had cartilaginous skeletons. The vertebral column and other portions of the skeleton were not ossified (i.e. changed to bone).

(3) All had vertebrated tail fins. The vertebral column extended through the tail fin and gave off fin rays to support a lobe above and below. Sometimes this tail fin was symmetric and sometimes asymmetric. The asymmetric form is regarded as the more primitive. Most modern fishes (teleosts) have non-vertebrated tail fins, the fin rays being sent out from a plate at the end of the vertebral column.

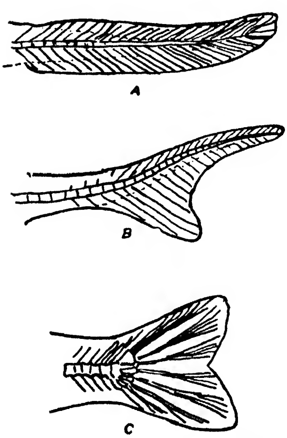


FIG. 138. Types of fish tails: *a*, vertebrated symmetric; *b*, vertebrated non-symmetric; *c*, non-vertebrated symmetric. (Redrawn after Le Conte.)

(4) They were generalized types. "Along with their distinctive fish-characters, they combined others which connect them with higher vertebrates, especially amphibians, and still others which are found in the embryos of teleosts. The most important connecting characters . . . are: (*a*) An external protective armor of thick bony plates or scales such as were possessed by early amphibians, and by many reptiles of the present time; (*b*) Large conical teeth channelled at the base, and of labyrinthine structure on section. This structure was very marked in early amphibians; (*c*) A cellular air bladder . . . capable of being used to some extent as a lung; (*d*) In many cases paired fins which had something like jointed legs running through them; (*e*) The tail fin vertebrated as in reptiles."[1] The most prominent embryonic characters were the cartilaginous skeleton found only in the embryonic stage of the typical modern fishes (teleosts), and the vertebrated character of the tail fin, the tail of the modern teleost successively passing from the asymmetric vertebrated stage, to symmetric vertebrated, and finally to symmetric non-vertebrated (Fig. 138).

Generalized or synthetic types, so well illustrated by Devonian fishes, are of great importance in considering the evolution and geological history of organisms.

[1] J. Le Conte: *Elements of Geology*, p. 356.

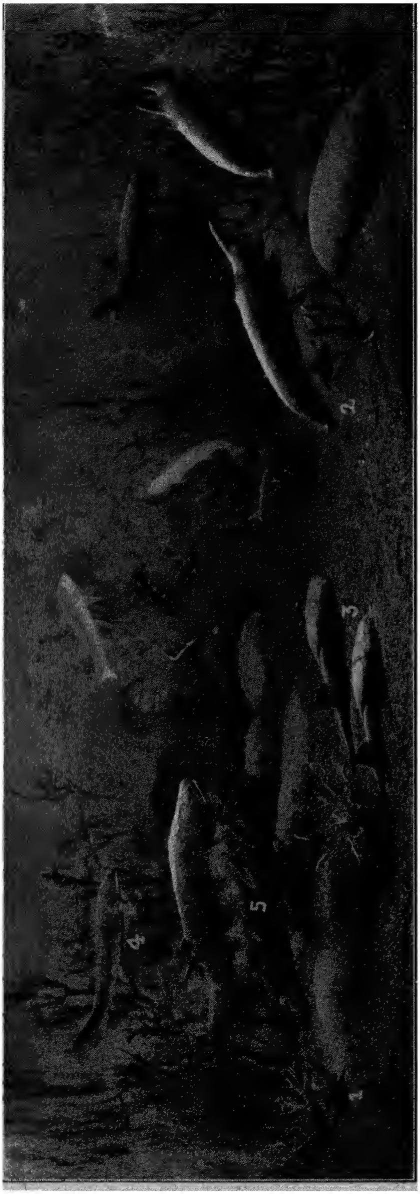


FIG. 139. A "Fossil Aquarium" showing restorations of Devonian fishes and ostracoderms found in a single layer of the "Old Red Sandstone" of Scotland. *1*, an ostracoderm (*Pterichthys*); *2*, a dipnoan (*Dipterus*); *3*, an arthrodiran (*Coccosteus*); *4*, a ganoid (*Osteolepis*); *5*, a crossopterygian (*Holoptychius*); and others. (Courtesy of American Museum of Natural History.)

Amphibians. These animals rank next above the fishes, having evolved from certain types of the latter in Middle Paleozoic time. Footprints and some bones are known from the Devonian rocks, but Mississippian, Pennsylvanian, and Permian strata have yielded numerous and varied fossil forms. Then as now they breathed by gills when young and by lungs when adult, and they had large, bony, rooflike skull plates. Amphibians are relatively unimportant among the vertebrates of today, but in Later Paleozoic time they were important, reaching their culmination in numbers, complexity, and diversification of size and forms.

The appearance of amphibians, representing the first known land vertebrates as early as the Devonian, marked a very significant advance

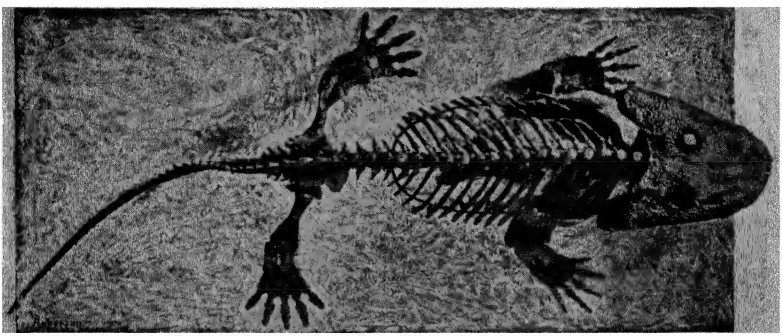


FIG. 140. A Pennsylvanian amphibian (labyrinthodont), *Eryops*. This creature attained a length of 6 or 8 feet. (Courtesy of the American Museum of Natural History.)

in the evolution of life. The first skeletal remains of Devonian amphibians were found in Greenland in 1931. They were popularly called "four-legged fish", but they are really primitive amphibians, in certain respects closely related to the lobe-finned ganoid fishes from which they were no doubt descended.

All Mississippian and Pennsylvanian amphibians are often classed together as *stegocephalians,* so-called because of the relatively large, bony, rooflike plates of the skulls.

The Pennsylvanian was probably the culminating period of the amphibians. In regard to the principal forms of Pennsylvanian amphibians, S. W. Williston[1] has said: "The predominating types of the

[1] *Outlines of Geologic History,* 1910, p. 164.

Pennsylvanian were what we usually call the *branchiosaurs* and the *microsaurs,* for the most part small or very small creatures, at least as small as their nearest living relatives of the present time, the salamanders. We are quite justified in the belief that their habits in general

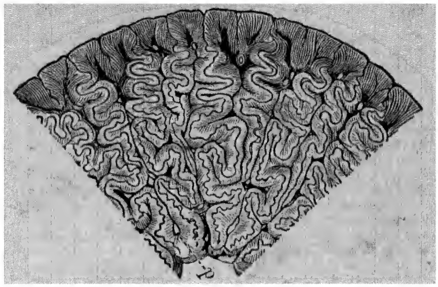


FIG. 141. Transverse section of a labyrinthodont tooth. (After Owen from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

were not greatly unlike these descendants, rather sluggish creatures living about or in the water, for the branchiosaurs at least passed through larval stages. They were more or less protected by an external bodily armor against their enemies, whether of their own or other kinds, in all

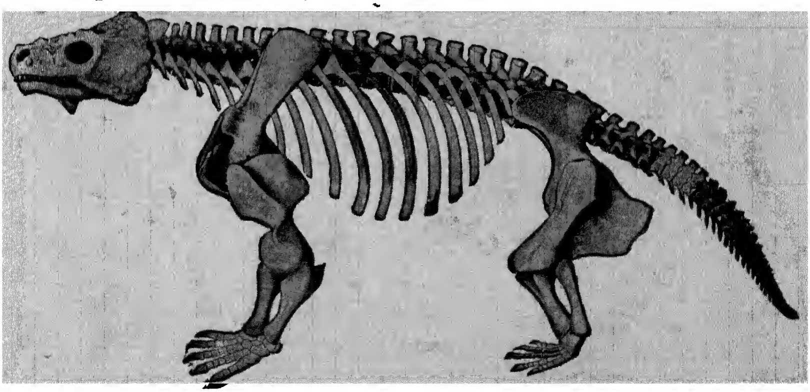


FIG. 142. A Permian reptile, *Pareiasaurus serrideus.* This creature reached a length of over 8 feet. (After Broom, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

probability terminating their existence as distinctive types long before the close of the Paleozoic. But among them there were some classed with the heterogeneous group which we call microsaurs, which had made a very distinct advance, both toward a higher existence and away from

the water. . . . Some lost the dermal armor completely and became fleet of movement, as is evidenced by the structure of the limbs, limbs mimicking in form and structure so closely those of modern quick-running lizards as to be practically indistinguishable."

The *labyrinthodonts,* and certain other closely related forms, comprised another important group of Pennsylvanian amphibians. They are so named because of the peculiar, labyrinthine, internal tooth-structure (Fig. 141). They were the gigantic land vertebrates of the period, some having reached a length of 7 or 8 feet (Fig. 140).

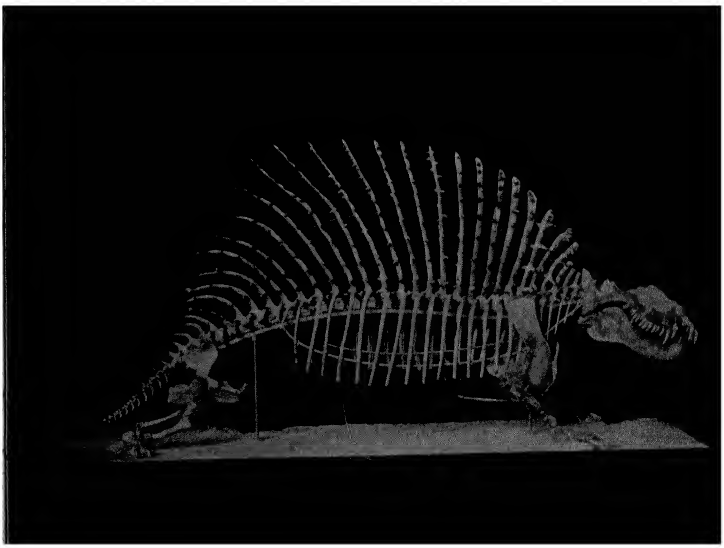


FIG. 143. A Permian reptile (pelycosaurian), *Naosaurus claviger.* (After Osborn, from Scott's "Geology," permission of The Macmillan Company.)

Permian amphibians were much like those of the Pennsylvanian, but some were even larger, new species were added, and more reptilian features were developed in some of them.

Reptiles. The abundance of true reptiles in the succeeding (Permian) period strongly suggests their earlier differentiation from the amphibians. According to Williston: "We may be assured that some of them (amphibians), before the close of the Pennsylvanian, were inhabitants of high-and-dry land regions where fleetness of movement, rather than obscurity, preserved them from their enemies, crawling

reptiles in everything save some insignificant technical details of their plates." More recent discoveries show that some primitive, true reptiles existed during the Pennsylvanian, but they were much like amphibians with short legs scarcely carrying their thickset bodies above ground, and with armor-plated heads like the stegocephalian amphibians.

There may be doubt about the existence of true reptiles in the Pennsylvanian, but there is no question about the abundant reptilian records of the Permian. They developed in a remarkable manner, so that before the close of the period several important subclasses or orders, represented by many individuals, were evolved. Some of the reptiles already began to show rather distinct mammalian characteristics. The accompanying figures will give a good idea of two important Permian forms.

CHAPTER XVIII

SUMMARY OF PALEOZOIC HISTORY AND LIFE

"We have defined geology as the history of the evolution of the earth. *Evolution,* therefore, is the central idea of geology. It is this idea alone which makes geology a distinct science. This is the coherent principle which unites and gives significance to all the scattered facts of geology—which cements what would otherwise be a mere incoherent pile of rubbish into a solid and symmetrical edifice. It seems appropriate, therefore, that at the end of the long and eventful Paleozoic era we should glance backward and briefly recapitulate the evidences of progressive change (evolution)." [1]

Paleozoic Rocks

Paleozic rocks are dominantly sandstones, conglomerates, shales, and limestones of typical, marine, sedimentary character, though continental deposits also are common, such as fresh-water, swamp, or lagoon deposits of the Pennsylvanian in the eastern Mississippi Basin and the "Red Beds" formed in great salt lakes of Permian age in the southwestern United States.

The marine strata furnish abundant evidence, by the presence of ripple and wave-marks, the coarseness of the clastic materials (conglomerates and sandstones), etc., that they were deposited in shallow (epeiric) seas, and never in really deep ocean water. Continental deposits are also abundantly represented.

In Europe the estimated maximum thickness of Paleozoic strata is 75,000 to 100,000 feet. It must be remembered, however, that this does not mean that such a great thickness of strata is present in any one locality, but rather that this represents the sum-total of the greatest thicknesses of the different formations of the continent.

A thickness of more than 25,000 feet of Paleozoic strata (largely clastic) actually piled layer upon layer may now be seen exposed in the

[1] J. LeConte: *Elements of Geology,* 5th Ed., p. 421.

highly folded and eroded Appalachians, while the maximum thickness of strata there must be between 40,000 and 50,000 feet. All seven systems are shown.

The Paleozoic group between the Appalachian and Rocky Mountains usually measures only a few thousand feet in thickness, and limestones are there relatively more abundant than clastic deposits, because of the generally greater distances from eroding lands where they acumulated. They are very little folded or faulted.

In the western United States, Paleozoic strata usually show a thickness of many thousands of feet, and limestones are there also prominently developed. Thus in eastern California (Inyo-Death Valley region) there are fully 35,000 feet of Paleozoic strata representing all of the seven systems. The strata are largely marine, including much limestone. They are highly folded and faulted. Fig. 144 shows a fine section of the Paleozoic group, involving all seven systems, with a thickness of fully 15,000 feet. Limestone also predominates there. It should not, however, be inferred that the Paleozoic is always so well represented in the west. In the Rocky Mountains and Basin and Range Province, the Paleozoic strata are generally more or less strongly folded and faulted, but in the Colorado Plateau they have been comparatively little disturbed.

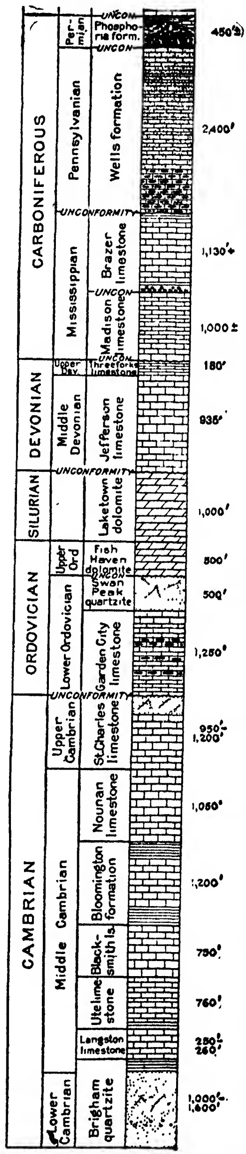


FIG. 144. Columnar section showing the character and thickness of the formations, representing all of the seven periods of the Paleozoic, in southeastern Idaho. This area, in the great Cordilleran geosyncline, was submerged during nearly all of the larger North American marine floods. Note the predominance of limestone. The total thickness of the formations is over 15,000 feet. (After G. R. Mansfield, U. S. Geological Survey.)

The only large masses of igneous rocks of Paleozoic age are listed beyond under the caption "Igneous Activity."

Physical History

Relations of Land and Sea. During Paleozoic time the most persistent, large, land areas (so-called "positive elements") which tended to stand out above the various epeiric seas were as follows: *Appalachia,* along the eastern side of the continent; *Antillia,* including the region of the West Indies; *Canadia,* which covered much of northeastern Canada and Greenland; *Cascadia,* which extended from northern California to Alaska; *Mexicoia,* which covered the general region of Mexico; and *Siouxia,* a generally smaller and less well-defined area in the southwestern interior of the United States.

Lying between the four lands just mentioned, were the wide areas which tended to be flooded repeatedly (so-called "negative elements"). The Appalachian and Cordilleran geosynclines, in the eastern and western parts of the continent, respectively, were the most persistent and well-defined portions of the negative areas.

Fig. 145 is a highly generalized map of North America showing a rather typical arrangement of the Paleozoic positive and negative areas just described, and also the Appalachian and Cordilleran geosynclines, from Middle Cambrian to Middle Pennsylvanian time.

There were many oscillations of level between land and sea, causing repeated emergence and submergence of large and small areas, varying from a condition of the continent wholly land to fully two-thirds flooded. Generally considered, the Paleozoic lands were relatively low and featureless—very different from the lands of today—and the epeiric seas were shallow. There were, of course, more or less locally and at various times, considerable elevations of the land.

In this brief summary only certain very important geographic changes will be mentioned. The paleogeographic maps should be reviewed.

The era opened with North America a land area. Early in the Cambrian, marine waters, in the form of long sounds, extended through the Appalachian and the Cordilleran regions. In the Late Cambrian at least one-third of the continent was under water, but at the close of the period all was land.

There were three great marine invasions during the Ordovician, most extensive of all probably late in the period when fully two-thirds of the continent was submerged.

Beginning with the continent all land, the Silurian was marked by several important marine transgressions, the one in the middle of the

period having covered fully one-half of the continent. Very little sea water remained at the close of the period.

An outstanding feature of the Devonian was a more or less steady advance of the sea from the beginning of the period to a little beyond its middle when nearly one-half of the continent was submerged. A withdrawal of the sea left nearly all dry land at the close of the period.

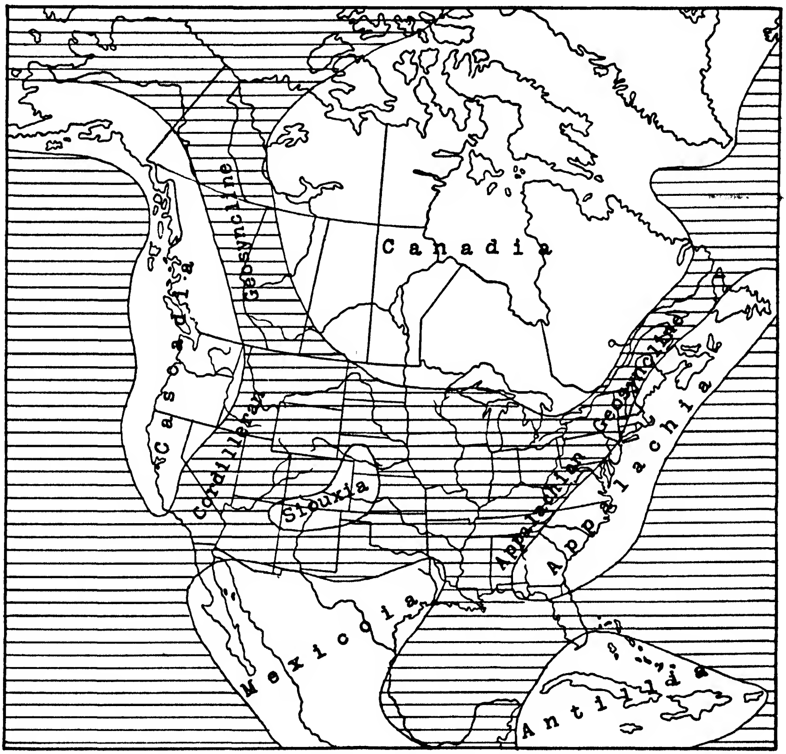


FIG. 145. A highly generalized map of North America showing a rather typical arrangement of the principal Paleozoic positive and negative areas, and also the Appalachian and Cordilleran geosynclines, from Middle Cambrian to Middle Pennsylvanian time.

About one-third of North America became submerged during earlier Mississippian time, followed by considerable retrogression of the sea in the midst of the period. Another extensive submergence marked later Mississippian time. Nearly all was land at the close of the period.

A great feature of Pennsylvanian time was a more or less progressive submergence of a considerable portion of the continent, beginning

in the east and spreading westward across the United States, and northward into southern Alaska. The great coal-forming swamps of the east were important. Practically all of the continent was land at the close of the period.

Beginning with a small Permian marine invasion in the southwestern United States, the sea spread until much of the western one-third of the continent was submerged in Middle Permian time. The sea diminished to disappearance in the Late Permian, leaving the continent all a land area.

Mountain-making. During the Paleozoic era there were four important movements in North America when rocks were folded into mountain ranges. The first was the Taconic Revolution at the end of the Ordovician when part of the eastern border of the continent was considerably folded and elevated. The second was the Acadian Revolution, which orogeny affected eastern New England and New Brunswick at the close of the Devonian. The third was the Ouachita Revolution in Oklahoma and Arkansas, in the midst of the Pennsylvanian. The fourth was the Appalachian Revolution, by far the grandest of all, when the whole Appalachian region from Alabama to the Gulf of St. Lawrence was greatly folded.

It is a significant fact that all of these important orogenic disturbances occurred within the southeastern one-fourth of the continent, this being in marked contrast with the great mountain-making disturbances of Mesozoic and Cenozoic times in western North America.

Igneous Activity. Paleozoic volcanic rocks occur in both the eastern and the western parts of the continent. More or less vigorous volcanic activity occurred at the following times and in the following regions: Ordovician in the Appalachian region, Newfoundland, and eastern Quebec; Silurian in Maine, New Brunswick, Nova Scotia, and southern Alaska; Devonian in Maine, New Brunswick, Nova Scotia, southeastern Quebec, and Alaska; Mississippian in the Klamath and Sierra Nevada Mountains of California, in Alaska, and in the Ouachita Mountains of Oklahoma; and Permian in Idaho, Nevada, northern California, and southern Alaska.

The only important plutonic igneous intrusions of Paleozoic age in North America seem to have been the considerable invasions of granite magma which accompanied the Acadian Revolution; and the great granite invasions which accompanied the Appalachian Revolution.

In Europe igneous activity was more frequent and widespread.

CLIMATE

The strongest evidence from the character and distribution of the organisms points to a temperate and rather uniform climate for most part over the globe during Paleozoic time.

Typical and widespread glacial deposits show that extensive areas, particularly in the southern hemisphere, were strongly glaciated toward the close of the era (Permian). Other deposits, more or less certainly of glacial origin, prove that at least local glaciers existed in some parts of the world during Devonian, Mississippian, and Permian times.

Certain deposits such as the "Red Beds," salt, and gypsum indicate at least local arid climatic conditions, as for example in northern Siberia (Ordovician); New York (Salina epoch of the Silurian); Michigan, Montana, Nova Scotia, and Australia (Mississippian); and southwestern United States, western and central Europe, and other parts of the world (Permian).

LIFE HISTORY

Viewed in a broad way, the life of the Paleozoic was distinctly different from that of the succeeding Mesozoic or Cenozoic. Very few species and not many genera passed from the Paleozoic to the Mesozoic, and even the larger groups of organisms which did continue usually underwent important structural changes. Paleozoic organisms were the more primitive in structure, and it has been aptly said that they bear somewhat the same relation to the succeeding forms that the embryo does to the adult.

Of plants in the Earlier Paleozoic only the simplest seedless plants are known, while in rocks of Later Paleozoic age there are abundant records of higher seedless plants, such as filicales, arthrophytes, and lepidophytes, and also of the gymnosperms. Angiosperms (typical flowering plants) are wholly unknown from the Paleozoic, and even the later forests and foliage of the era must have presented a gloomy appearance because of the lack of true flowering plants as compared with today.

The animals of the Paleozoic were predominantly invertebrates, though fishes were common in the Devonian and later periods, and amphibians and reptiles appeared in the later periods. Among the most common and characteristic types of invertebrates were graptolites, corals, stalked echinoderms (pelmatozoans), bryozoans, brachiopods, tetrabranch cephalopods (nautiloids especially), trilobites, and eurypterids. Certain of the higher arthropods such as spiders, myriapods (centi-

TABULAR SUMMARY OF PALEOZOIC LIFE

	Plants	*Protozoans*	*Porifers and Cœlenterates*	*Echinoderms*
PERMIAN	Thallophytes. Bryophytes. Filicales. Arthrophytes. Lepidophytes. Gymnosperms: Pteridosperms, cycads, cordaites, conifers.	Foraminifers: Very common. Radiolarians: Present.	Sponges: Present. Corals: Ancient Tetracoralla still common, but first Hexacoralla appear.	Cystoids: Become extinct. Crinoids: Greatly diminished. Asterozoans: Present. Echinoids: Present.
PENNSYLVANIAN	Thallophytes. Bryophytes. Filicales. Arthrophytes and lepidophytes: Common. Gymnosperms: Pteridosperms and cordaites: Common.	Foraminifers: Very abundant. Radiolarians: Present.	Sponges: Present. Corals: Similar to Mississippian but less common.	Cystoids: Rare. Blastoids: Become extinct. Crinoids: Declining. Asterozoans: Present. Echinoids: Rare.
MISSISSIPPIAN	Much like Devonian.	Foraminifers: Very abundant. Radiolarians: Common.	Sponges: Common. Graptolites: Very rare and become extinct. Corals: Cup and honeycomb forms only, and less prominent than in the Devonian.	Cystoids: Rare. Blastoids: Culminate and become rare. Crinoids: Culminate in numbers and species. Asterozoans: Not common. Echinoids: Common.
DEVONIAN	Thallophytes: Seaweeds and diatoms. Bryophytes? Filicales. Arthrophytes. Lepidophytes. Gymnosperms: Simple types, e.g., pteridosperms, cordaites.	Foraminifers: Present. Radiolarians: Present.	Sponges: Common. Graptolites: Decline almost to extinction. Corals: Cup and honeycomb forms greatly increased in numbers and size; chain corals rare and become extinct.	Cystoids: Much diminished. Blastoids: Still uncommon. Crinoids: Still increasing. Asterozoans: Abundant. Echinoids: Present.
SILURIAN	Thallophytes: Seaweeds. Bryophytes? Pteridophytes: Ferns, but rare.	Foraminifers: Present. Radiolarians Present.	Sponges: Common. Graptolites: Diminished in numbers and species. Corals: Increase in prominence and chain-corals attain their climax.	Cystoids: Prominent. Blastoids: Still rare. Crinoids: Increase in numbers and species. Asterozoans and echinoids: Increase.
ORDOVICIAN	Thallophytes: Seaweeds. Bryophytes? Higher seedless plants? Fernlike plants (Psilophytales).	Foraminifers: Abundant. Radiolarians: Abundant	Sponges: Very common. Graptolites: Reach climax in numbers and species. Corals: Common, e.g., cup, honey-comb, and chain forms.	Cystoids: Culminate. Blastoids: First appear and rare. Crinoids: First appear and common. Asterozoans and echinoids: First appear.
CAMBRIAN	Thallophytes: Algæ. Primitive land-plant spores?	Foraminifers: Present.	Sponges: Common. Hydrozoans: Graptolites and jellyfishes, both common. Corals: Present?	Cystoids: Primitive forms and rare.

pedes), and insects did not appear until the era was rather well advanced.

The accompanying chart has been devised by the writer for the purpose of bringing together the salient facts in the organic history of the

TABULAR SUMMARY OF PALEOZOIC LIFE—*Continued*

Molluscoids	*Mollusks*	*Arthropods*	*Vertebrates*
Bryozoans: Abundant. Brachiopods: Still common, with new species; straight-hinged forms still prevail.	Pelecypods: Greatly increased in numbers and species. Gastropods: Common. Cephalopods: Some earlier forms still persist, but ammonoids (e.g., Waagenoceras) now common and more complex.	Trilobites: Very rare and become extinct. Eurypterids: Become extinct. Insects: Much like the Pennsylvanian.	Fishes and amphibians: Much like the Pennsylvanian, but with new species. Reptiles: Many representatives of the lower orders.
Bryozoans: Common. Brachiopods: Still declining, but fairly common; straight-hinged forms prevail.	Pelecypods: Still increasing. Gastropods: Common and first land forms appear. Cephalopods: Similar to Mississippian, but nautiloids declining and ammonoids more complex.	Trilobites: Rare. Eucrustaceans: Present. Arachnids: Eurypterids still declining; spiders; scorpions. Myriapods: Common. Insects: Common and large; simpler types only.	Fishes: Much like the Mississippian. Amphibians: Culminate, e.g., stegocephalians. Reptiles: Amphibian-like forms.
Bryozoans: More abundant than in the Devonian. Brachiopods: Declining but still common and with many new species; mostly straight-hinged forms.	Pelecypods: More common than before. Gastropods: Common. Cephalopods: Much like the Devonian, but coiled nautiloids culminate and ammonoids are more complex.	Trilobites: Rare. Eucrustaceans? Arachnids: Eurypterids declining. Myriapods: Present. Insects: No fossils.	Fishes: Selachians increasing; dipnoans declining; arthrodirans declining; ganoids increasing. Amphibians: Present.
Bryozoans: Present. Brachiopods: Culminate in numbers and species; many new forms added; mostly straight-hinged forms.	Pelecypods and gastropods: Much like the Silurian. Cephalopods: Most earlier forms persist, but ammonoids first appear, e.g., Goniatite.	Trilobites: Decline markedly. Eucrustaceans: Common. Arachnids: Eurypterids declining, but still notably large; spiders. Myriapods: First known. Insects: Unknown.	Ostracoderms: Culminate and become extinct. Fishes: Very profuse, e.g. selachians, dipnoans, arthrodirans and ganoids. Amphibians.
Bryozoans: Abundant. Brachiopods: Prominent in numbers and species; nearly all straight-hinged forms.	Pelecypods and gastropods: Common and much like Ordovician. Cephalopods: Common and much like Ordovician, but coiled nautiloids predominate.	Trilobites: Still common. Eucrustaceans: Similar to Ordovician. Arachnids: First scorpions; eurypterids culminate in numbers, species and size (?).	Ostracoderms: Rare, small and primitive. Fishes: Selachians of primitive character and rare.
Bryozoans: Abundant. Brachiopods: More complex, larger, and abundant; articulates prevail; and nearly all are straight-hinged forms.	Pelecypods: Fairly common. Gastropods: Common. Cephalopods: Very prominent and all are nautiloids, e.g., Orthoceras, Cyrtoceras, Trochoceras and Trocholites.	Trilobites: Culminate in numbers and species. Eucrustaceans: Few and simple. Eurypterids: Present.	Ostracoderms: Marking first appearance of vertebrates: specimens rare and very fragmentary.
Bryozoans: Absent Brachiopods: Small, thin-shelled; inarticulates prevail; some articulates in the Upper Cambrian.	Pelecypods: Not known. Gastropods: Rare, simple. Cephalopods: Rare, small and simple; all nautiloids, e.g., Orthoceras and Cyrtoceras.	Crustaceans: Trilobites common and usually highly segmented and with small tail plates; some very simple forms. Eurypterids: Rare.	None.

Paleozoic era. Period by period the principal evolutionary changes in the sub-kingdoms and classes of organisms are shown.

"A study of the Paleozoic faunas of North America shows that they were derived from three permanent oceanic realms. According to

Schuchert, these were, in their order of persistence, the Gulf of Mexico mediterranean, which in reality is but the southern part of the northern Atlantic; the Pacific; and the Arctic. The faunas of the northern part of the north Atlantic were as a rule confined to the northeastern part of North America, though at times they spread into the interior basin. Pacific faunas at times spread completely across the continent to the foot of Appalachia. Arctic waters pulsated southward along the middle region of the continent far into the United States during the Ordovician and Silurian periods, and less positively at other times. Faunas from the Gulf of Mexico frequently spread far throughout the Mississippi Valley and Appalachian areas. They were at times also tinged with south European or South American forms." [1]

It seems to be a well established fact that profound changes in the natural environment have produced fundamental changes in the plant and animal realms. Thus the late Paleozoic and early Mesozoic was a time of one of the most profound and far-reaching physical disturbances in the known history of the earth. Great mountains were being made in many parts of the world, particularly in eastern North America and in Europe; the lands were much increased in size and height; one of the two greatest known Ice Ages was a feature of the Permian; and the ocean waters were affected in various ways. These physical changes in turn caused climatic changes, altered habitats of plants and animals, and modified sources of food for the animals. Accompanying these changes, the giant lycopods, seed ferns, and cordaites became extinct, while higher plants, such as cycads and conifers, began to clothe the earth. Large groups of animals, such as Tetracoralla, blastoids, orthoceras, trilobites, and eurypterids disappeared from the waters; amphibians culminated; and Hexacoralla, insects, reptiles, and mammals made their appearance.

It is a very significant fact, from the standpoint of evolution of life on the planet, that very few if any species of either plants or animals of Paleozoic time have continued to exist to the present day. In other words, since the Paleozoic era closed, all life, in regard to its myriads of species, has undergone a practically complete revolution.

[1] G. R. Mansfield: U. S. G. S., *Prof. Paper* 152, 1927, p. 177.

THE MESOZOIC ERA

CHAPTER XIX

ROCKS AND PHYSICAL HISTORY OF THE TRIASSIC

Origin of Name and Subdivisions

The name "Triassic" was given because of the threefold, extensive development of the rocks of the system where first studied in Germany. It so happens, however, that the German Triassic strata are not typical of the system, as shown by later studies in other parts of the world.

The following table gives a general idea of the main subdivisions in four parts of North America:

	Idaho	*California*	*Colorado Plateau*	*Massachusetts*
Upper Triassic	Deadman ls. Higham ss. Timothy ss.	Swearinger sh. Hosselkus sh.	Chinle ss., sh. Shinarump cg.	Newark cg., ss., sh.
Middle Triassic	(Missing) Portneuf ls.	Pit sh.	(Missing)	(Missing)
Lower Triassic	Fort Hall fm. Ross Fork fm. Woodside fm.	Shale in Inyo Mts.	Moenkopi sh., ss.	(Missing)

Distribution and Description of the Rocks

General Distribution. The accompanying map (Fig. 146) shows the surface distribution of both the Triassic and Jurassic rocks in North America. The Atlantic Coast areas are wholly Triassic; the California areas are mainly Jurassic; and the remaining areas include both Triassic and Jurassic rocks which have usually not been carefully separated. There is no reason whatever to believe that Triassic rocks were ever deposited over Canada except along the western coast and to a slight extent in Nova Scotia. Likewise it is not known that Triassic rocks

ever occurred in the Mississippi Basin except immediately east of the Rocky Mountains. This is in marked contrast with the Paleozoic systems. Accordingly, the present concealed Triassic rocks and areas of

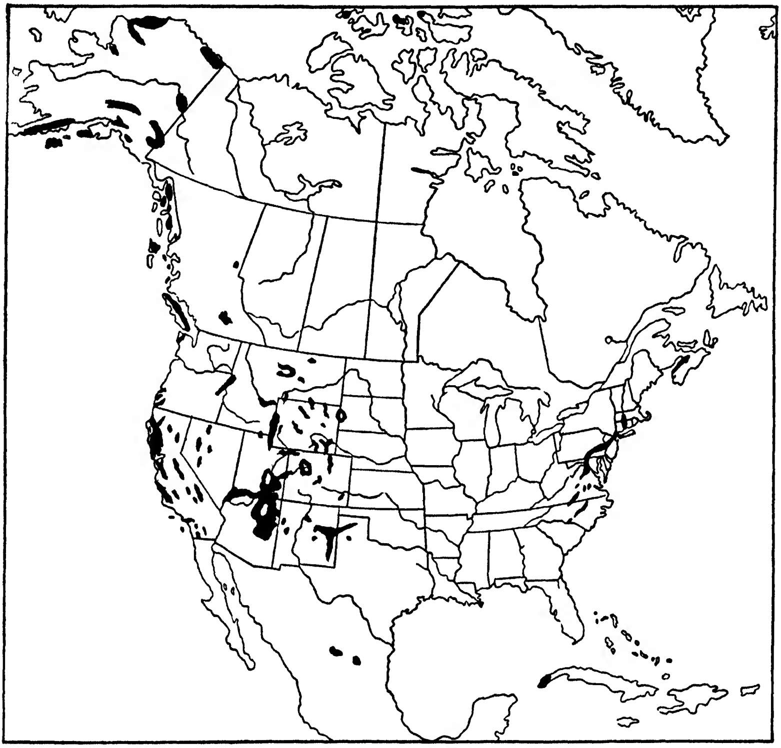


FIG. 146. Map showing the surface distribution (areas of outcrops) of Triassic and Jurassic strata in North America. Some areas of doubtful age and extent not shown in British Columbia. All Atlantic Coast areas are Triassic. In much of the western United States the Triassic and Jurassic have not yet been satisfactorily separated.

their former presence are largely confined to the regions of existing outcrops.

Rocks of the Atlantic Coast. These rocks (*Newark* series) are seen on the map to occupy comparatively small, narrow areas just east of and parallel to the Appalachian Mountain range from southeastern New York to South Carolina, and farther northward in the Connecticut River Valley and in Nova Scotia. In the northern areas the rocks are

sandstones and shales, with some coarse conglomerates, especially at the base. Because of their prevailing red color and general resemblances to the "Old Red Sandstone" (Devonian) of Scotland, they have been called the "New Red Sandstone." Many of the beds show suncracks, raindrop pits, ripple marks, and footprints and remains of land reptiles (dinosaurs). In Virginia and the Carolinas the rocks have a similar lithologic character, though the red color is not so common, and some workable coal beds occur. The fossils, which are mostly plants in the dark shales, point to the Upper Triassic age of the Newark series.

The rocks of the series are nearly everywhere somewhat folded, tilted, and extensively fractured by normal faults, and they also contain numerous lava flows, intrusive sheets, and dikes of dark basaltic rock (Figs. 147, 152). A remarkable feature is the great thickness of the rocks in these narrow belts, fully 3000 feet in Virginia; 7000 to 10,000 feet in the Connecticut Valley; and 10,000 to 15,000 feet in New Jersey.

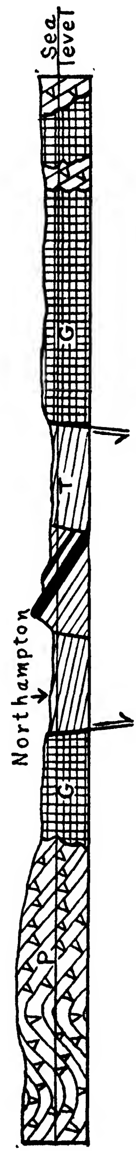


FIG. 147. Structure section across the Triassic Basin of the Connecticut Valley near Northampton, Massachusetts, showing the tilted and faulted character of the rocks. Strike of the section, northwest. Length of section, about 40 miles. P = Paleozoic schist; G = late Paleozoic granite; T = Triassic strata, with sheets of lava (black layers). From the author's "Geological History of the Connecticut Valley of Massachusetts.")

Rocks of the Western Interior. The Triassic strata of the western interior region are distributed over nearly the same areas as the Permian, and in many places the rocks of these two systems are not at all sharply separated. All the known Triassic rocks of the western interior of the United States are located within the cross-lined area on map, Fig. 151. They are much like the Permian of this region, but they are even more typical of the so-called "Red Beds." Sandstone and shale, with some conglomerate, limestone, and gypsum, are the predominant rocks. Some of these rocks are of restricted marine origin, but most of them are of either salt-lagoon or terrestrial origin. Their thickness varies from a few hundred feet in

the eastern part of the western interior to 2500 feet or more in Utah and Arizona. The Triassic strata are locally much folded in the mountains, but over wide areas they are nearly horizontal.

Triassic rocks are wonderfully and widely exposed in the Colorado Plateau where the nearly horizontal strata lie from 5000 to 10,000 feet above sea level. Because of their high degree of sculpturing and coloring, as in the Painted Desert of Arizona, they form a striking feature of the landscape. The Triassic formations of the Colorado Plateau (see preceding table) are a variable assemblage of shale, sandstone,

FIG. 148. Tilted Triassic shale and sandstone in the Connecticut Valley, near Holyoke, Massachusetts.

conglomerate, limestone, and gypsum, reaching a total thickness of 2000 to 3000 feet. Petrified wood is abundant, as in the Petrified Forest of Arizona (Fig. 185).

In southeastern Idaho the Triassic system is well represented, there consisting of about 5000 feet of limestone, shale, and sandstone.

In Wyoming, Colorado, and New Mexico the Triassic system consists largely of shales and sandstones, usually red, and often upturned along the flanks of the mountains. Upturned edges of Triassic strata completely surround the Black Hills of South Dakota.

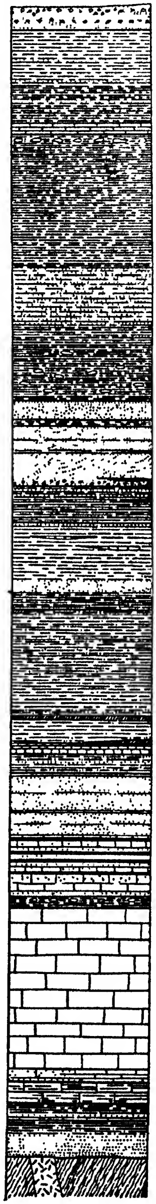
System	Kind of Rock	Columnar Section	Thickness in Feet
Oligocene	sand and gravel		25–150
Cretaceous	gray shale limestone dark shale and sandy-shale		1390
	red and buff sandstone gray and buff shale		325–590
Jurassic	red and buff sandstone and shale		325
Triassic	red shale and gypsum		500+
Permian	limestone and red sands		100–120
Pennsylvanian	white sandstone gray to red limy sandstone		500+
Mississippian	red shale gray limestone		650
Ordovician	pink limestone		80
Cambrian	shale sandstone		100–300
Pre-Cambrian	schist, granite		

FIG. 149. Columnar (geologic) section showing ages, character and thickness of strata in northeastern Wyoming. Note the prevalence of "Red Beds" toward the middle of the section. (After Darton, U. S. Geological Survey, Folio 127.)

Rocks of the Pacific Coast. These include the only true marine Triassic rocks of North America, and they are there extensively developed with practically all portions of the system from oldest to youngest well represented, particularly in California and Nevada. The rocks consist mostly of marine shales, limestones, conglomerates, and sandstones, often associated with much volcanic material. These rocks are often more or less metamorphosed, as in the Sierra Nevada Mountains. The Triassic rocks of the Pacific Coast are usually several thousand

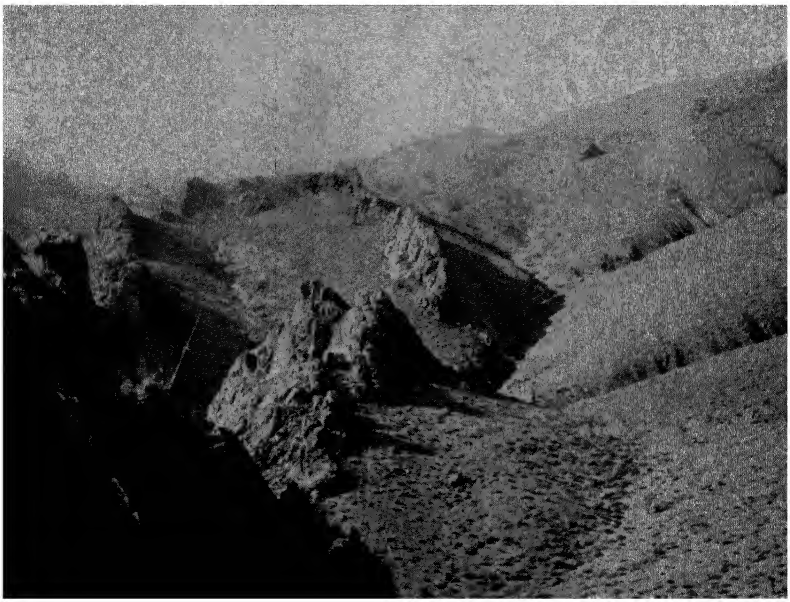


FIG. 150. Steep-dipping Triassic shale and limestone (bold outcrops) in the Inyo Mountains, near Keeler, California. (Photo by A. R. Whitman.)

feet thick, reaching a maximum of fully 13,000 feet in British Columbia. The rocks are usually much folded and often faulted.

In California, Nevada, Alaska, and British Columbia the system contains great quantities of igneous material, mainly lavas and tuffs, reaching total thicknesses of thousands of feet.

In central-eastern California (Inyo Mountains) Lower and Middle Triassic shales and limestones 1500 feet thick are overlain by Upper Triassic shales and tuffs 5000 feet thick. In northern California the Lower Triassic seems to be missing, but Middle Triassic shale and

Upper Triassic limestone are several thousand feet thick. In southern Nevada, the Permian system is more than 20,000 feet thick.

Physical History

Atlantic Coast. *Basins of Deposition.* The map, Fig. 146, shows the areas of continental deposition in eastern North America during Late Triassic time. These were all in the general Appalachian region. The non-marine formations (Newark series) of Upper Triassic age clearly show by their distribution and mode of occurrence that they were deposited in a series of long, troughlike basins. Because these troughs were situated between two great land masses—Appalachia and the newly formed Appalachians—the conditions were very favorable for rapid accumulation of thick deposits in them. The great thickness of the strata (maximum, 2 miles or more) strongly points to a subsidence of the basin floors while the deposition was in progress. Most of the rocks are well stratified. The generally red color and freshness of the material in the formations indicate that the climate of the time was arid or semi-arid, and the presence of sun cracks, ripple marks, and tracks of land animals at many horizons show that the beds were laid down in part on land, but mostly under shallow water, such as flood-plains and playa lakes, where frequently changing conditions often allowed the surface layers to lie exposed to the sun. The Newark series generally consists of three formations—a very coarse conglomerate and conglomeratic sandstone upon which lie in turn sandstone and shale formations.

A conception of the origin and filling of the Triassic basins may be gained from the following statements which were written in regard to the Connecticut Valley of Massachusetts. By the opening of Late Triassic time the great, new mountains of eastern North America had been considerably reduced by erosion. Then a sinking of the basin area began. "At first the sinking of the basin floor was probably a slow down-warping process such as is known to have taken place in many districts during geological time. This original down-bending of the Triassic Basin is best explained as a continuation (or renewal) of the Appalachian Mountain folding, this view being supported by the fact that all of the Triassic basins of sedimentation from Nova Scotia to North Carolina follow exactly the trend of the Appalachian folds. As the trough sank the adjacent lands were rejuvenated by elevation. Streams entering the basin from the growing highlands were renewed in activity, and they carried loads of coarse material which accumu-

lated on the floor of the low-level basin. The load of accumulating sediments probably aided or accentuated the down-bending process."[1] The great thickness of the very coarse materials, especially along the sides of the basin, leads to the conclusion that the margins of the basin must have been high and very steep during the whole time of the de-

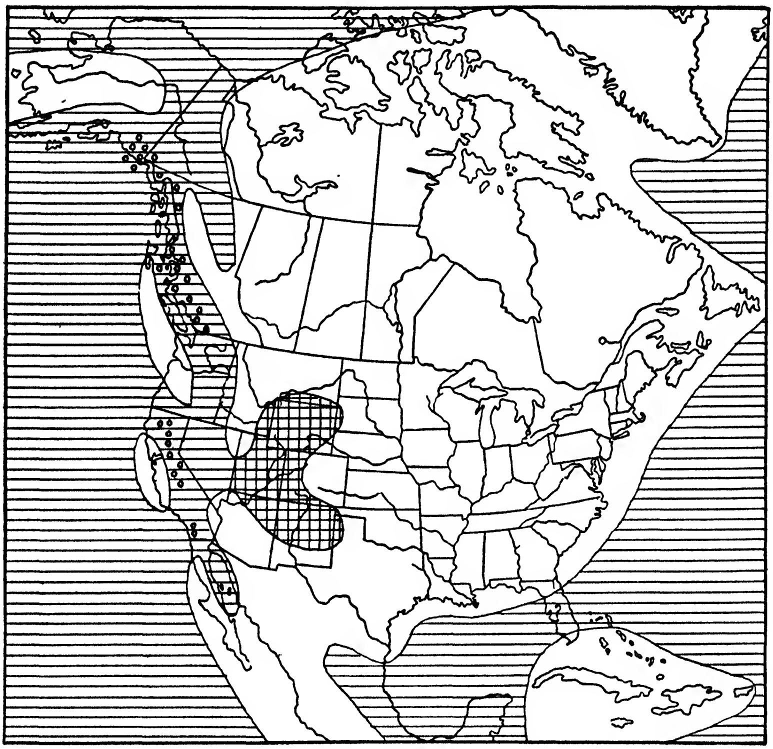


FIG. 151. Generalized paleogeographic map showing sea and land areas in North America during early Late Triassic time. This was the greatest Triassic sea. White areas, land; ruled areas, sea; cross-ruled areas, partly modified marine and partly continental conditions. Small circles show volcanic islands in the western sea. Principal data (modified) from maps by B. Willis, C. Schuchert, and E. B. Branson.

position of these materials, else the streams would not have been swift enough to transport the coarse debris. Such very steep valley-sides could not, however, have resulted from simple down-warping. More

[1] W. J. Miller: *Geological History of the Connecticut Valley of Massachusetts,* 1921, pp. 36-37.

than likely, therefore, normal faults developed on the sides of the subsiding, filling basin, and the subsidence was then largely a more or less intermittent sinking of the fault-block. The present-day structure of the valley is that of a sunken fault-block made up of minor tilted blocks (Fig. 147).

Volcanic Activity. During the time of the formation of the Newark beds, there was considerable igneous activity, as shown by the occurrence of sheets of igneous rocks within the mass of sediments. In some cases

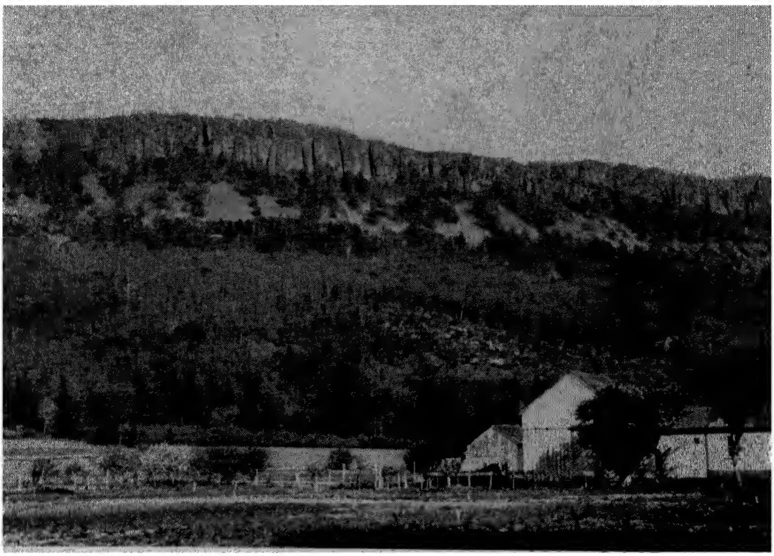


FIG. 152. The steep western front of the Holyoke Range as seen from Easthampton, Massachusetts. The upper portion is columnar lava of Triassic age, and this rests upon Triassic red sandstone.

true lava-flows with cindery tops were poured out on the surface and then became buried under later sediments, while in other cases the sheets of molten rock were forced up either between the strata or obliquely through them, thus proving their intrusive character. As a result of subsequent erosion, these igneous rock masses often stand out conspicuously as topographic features. Perhaps the most noteworthy of these is the great igneous rock sheet, part of which outcrops to form the Palisades of the Hudson River, and which altogether outcrops for a distance of 70 miles. The molten rock first broke through the strata and then crowded its way along parallel to them. Another fine ex-

ample is the so-called Holyoke Range of Massachusetts (Fig. 152) regarding which Emerson says: "The accumulation of sediments was interrupted by an eruption of lava through a fissure in the earth's crust, which opened along the bottom of the basin. The lava flowed east and west on the bottom of the basin, as tar oozes and spreads from a crack and solidified in a sheet which may have been 2 or 3 miles wide and about 400 feet thick in its central part. This is the main sheet or Holyoke diabase."[1] In both regions just mentioned, the contraction of

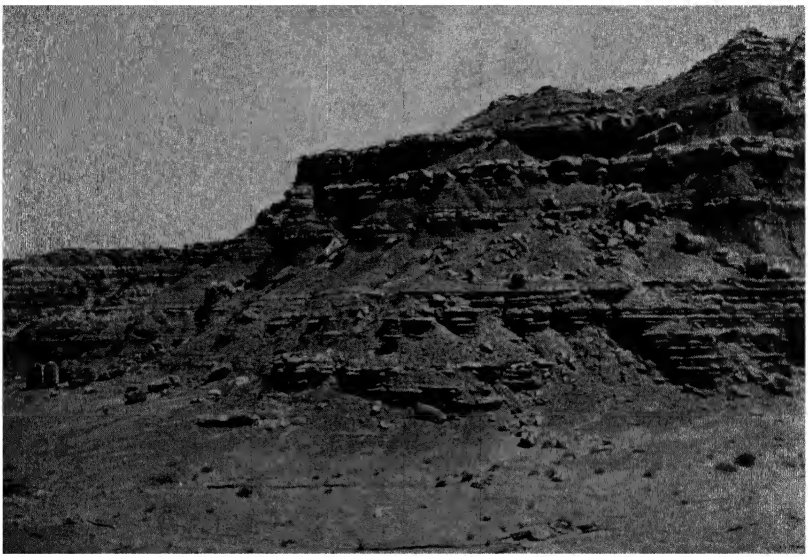


FIG. 153. Horizontal "Red Beds" consisting of interbedded red sandstone and shale with numerous concretions. Near Tuba City, northern Arizona.

the cooling masses often expressed itself by breaking the rock into great and small, crude, nearly vertical columns, and hence the application of the term "palisades." The steep mountain sides or cliffs are due to the fact that the hard igneous rock is much more resistant to weathering and erosion than the sandstone above and below it (Fig. 152).

Western Interior. In Early Triassic time the Pacific waters spread over northern, eastern, and southern California, much of Nevada, across Utah, and into southeastern British Columbia in the form of a gulf. Typical "Red Beds" were deposited extensively east of the gulf as far as

[1] B. K. Emerson: U. S. G. S., *Holyoke Folio* No. 50, p. 3.

western Nebraska. During the Middle Triassic, marine conditions did not extend beyond Nevada. Late Triassic time was marked by the development of a large lagoonal basin in the western interior of the United States. This basin seems to have been a more or less cut off arm of the sea, connected with the Pacific across southern Nevada (see Fig. 151). Very typical "Red Beds," indicating aridity of climate, were extensively developed in this basin. Modified marine, great salt lagoon, salt lake, and even terrestrial conditions seem to have prevailed from time to time in

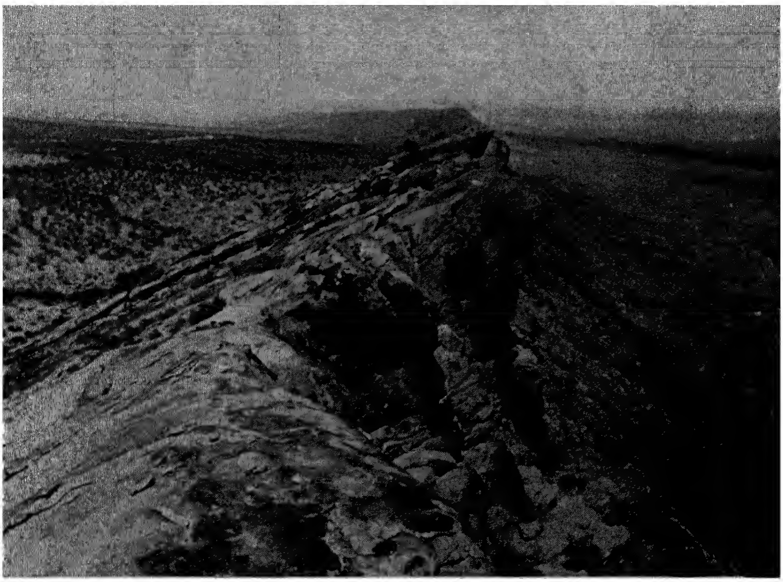


FIG. 154. A long ridge (hogback) consisting of strongly tilted Triassic sandstone. Northeast of St. George, Utah.

this basin. In various places, such as the Petrified Forest region of Arizona, tree trunks were carried by sediment-laden streams from higher lands and buried in basins of deposition. The tree trunks became petrified and now often exposed to view as explained in connection with Figures 184 and 185.

Pacific Coast. Viewed broadly, there was a progressive submergence of much of the Pacific Coast of North America during Triassic time. Early in the period most of California and Nevada were submerged under the sea; in the middle of the period there were added em-

bayments over part of western British Columbia and southern Alaska; and in the Late Triassic much of the Pacific Coast area from central Lower California to northern Alaska was under the sea. Figure 151 shows the extent of this the greatest North American Triassic sea.

Volcanic activity took place on a tremendous scale in much of California, western British Columbia, and southeastern Alaska, as proved by the direct association of thousands of feet in thickness of lavas and tuffs with marine Triassic strata. Figure 151 gives a general idea of the locations of these volcanoes, some of which were submarine and some volcanic islands.

Close of the Triassic (Palisades Disturbance). The Triassic closed in eastern North America with crustal disturbances which raised the basins of deposition of the Newark series into dry land, and broke the strata, and associated lavas and intrusive sheets, into a great series of tilted fault-blocks, thus leaving all of the eastern half or two-thirds of the continent dry land and undergoing erosion. This has been called the *Palisades Disturbance* because the rocks of the Palisades of the Hudson River were involved in the orogeny. The block mountains formed at this time were later leveled by erosion, after which the region was uplifted without faulting and eroded to the present-day condition (Fig. 147).

In the western interior the geographic conditions toward the close of the Triassic are as yet more doubtful because scarcity of fossils renders a separation of possible Jurassic strata from Triassic uncertain. The best evidence, however, points to continual deposition of "Red Beds" over much of the region.

Marine waters withdrew from the Pacific Coast region during latest Triassic time, and all of the continent was a land area.

Climate

The extensive areas of "Red Beds," often accompanied by salt and gypsum, in the western interior and eastern North America, northern and western Europe, and northern Africa show widespread aridity of climate in the northern hemisphere during the period. There is no evidence of glaciation, and the fossils indicate general mildness of climate, except at the close of the period when the temperature was distinctly lower than usual. Judging by the character and distribution of the fossils, the water of the Arctic Sea was appreciably cooler than that

of lower latitudes, so that climatic zones must have been defined to some extent at least.

Economic Products

Coal beds of some commercial value occur in the Triassic rocks of Virginia and North Carolina.

Enormous quantities of sandstone (the so-called "Triassic Brownstone") for building purposes have been quarried from the Newark series, especially in the Connecticut River Valley.

Gypsum of Triassic age is quarried in some of the western states.

Triassic salt beds are extensively worked in Germany and in England.

Some copper deposits occur in Triassic rocks of California and Alaska.

Foreign Triassic

Europe. As in America, so in Europe, the Triassic shows considerable development of both continental and marine facies. The Bunter series (1600 to 1800 feet thick) of Germany consists chiefly of red beds, such as sandstones and shales, with some salt and gypsum, clearly indicating deposition under arid climate conditions much like the western interior of the United States at the same time. The Muschelkalk of Germany is mostly a marine limestone formation up to 1000 feet thick, thus showing the presence of marine waters over the region, probably as an arm of the sea, similar to the Baltic Sea, as the fossils suggest. During part of this time, at least, salt lake conditions were restored as indicated by gypsum and salt in the midst of the series. During Keuper time conditions of deposition were much as during the Bunter, though late Keuper marine waters again transgressed the area. Bunter, Muschelkalk and Keuper are Lower, Middle, and Upper Triassic respectively.

In England, much of eastern Russia, and western and southern Spain, Triassic strata essentially like those of Germany are well developed.

In middle southern Europe the marine facies is widely developed, being mostly limestone (often dolomitic) and shales. The rugged peaks of the famous "Dolomites" or Tyrolean Alps have been carved out of this comparatively resistant dolomitic limestone, much of which was deposited by lime-secreting algae and corals.

Other Continents. The marine facies of the European Triassic continues eastward through much of southern Asia, there being an

unusually fine development of the system in the Himalayas. Triassic rocks, sometimes of continental origin, also occur in other parts of Asia as in Japan and eastern Siberia.

Triassic rocks are also known in Australia, New Zealand, North and South Africa, and South America, with coal-bearing strata in Argentina and Chile, and marine strata in the Andes.

In South Africa continental deposits (including "Red Beds"), thousands of feet thick, occur throughout an area of several hundred thousand square miles. Their deposition was followed by extensive volcanic extrusions, and, in very Late Triassic time, by tremendous and widespread intrusions of basic igneous rocks.

In southern Brazil, as in South Africa, very extensive "Red Beds" are overlain by great lava-flows.

CHAPTER XX

ROCKS AND PHYSICAL HISTORY OF THE JURASSIC

Origin of Name and Subdivisions

The rocks of Jurassic age are of peculiar interest because they comprise one of the very first systems whose subdivisions were carefully determined by the use of fossils, this work having been done in England early in the nineteenth century by William Smith, who is often called the father of historical geology. Smith applied the name "Oölitic" to the system because of the common occurrence of so much oölitic limestone, but this term later gave way to the term "Jurassic," so called from the Jura Mountains, between France and Switzerland, where the rocks of the system are unusually well exhibited and have been much studied. In Germany, too, much study has been devoted to this system.

The following table shows the main subdivisions in three important regions:

	California		Colorado Plateau			Rocky Mts.	
UPPER JURASSIC	Coombe ss. Trail tuff	Knox-ville	Morrison fm.			Morrison fm.	
	Lucky S sh. Cooks Canyon volc. Foreman fm.	Mari-posa	Summerville fm. Curtis fm. Entrada fm. Carmel ls., sh.		San Rafael	Stump ss. Preuss ss. Twin Creek ls.	Sundance
	North Ridge volc. Hinchman tuff. Bicknell ss.						
MIDDLE JURASSIC	Hull volc. Moonshine cg. Morman ss. Thompson ls., sh. Fant volc.		Navajo ss.	White Cliff	Glen Canyon	Nugget ss.	
LOWER JURASSIC	Hardgrave tuff Lilac sh. (Trail fm.) (Missing)		Kayenta fm. (Todilto) Wingate ss.	Vermilion Cliff	Glen Canyon	(Missing)	

Distribution and Description of the Rocks

General Distribution. Differing from all preceding systems, rocks of undoubted Jurassic age are wholly confined to the western part of

the continent. On map, Fig. 146, the considerable areas of outcrops shown in California and western Nevada are mostly Jurassic strata. Various areas are also known in northern and southern Alaska, and in southwestern Oregon. In the western interior numerous small and large areas of outcrops of Jurassic strata are known from northern Arizona and New Mexico northward through Utah, Colorado, southeastern Idaho, Wyoming, and into northern Montana. They show most extensively in the northern part of the Colorado Plateau.

FIG. 155. Structure section through a portion of the central Sierra Nevada Mountains, exhibiting the highly folded character of the Jurassic and late Paleozoic rocks. *Ccg, Cch* = Mississippian or Pennsylvanian slate and some limestone; *Jm* = Jurassic (Mariposa formation); *Am, Db, Sp* = Jurassic amphibolite, diabase, and serpentine respectively; *Na* = Tertiary lava; *Ng* = Tertiary gold-bearing gravel. Length of section about 11 miles. (After Lindgren, U. S. Geological Survey, Folio 66.)

The Jurassic, like preceding systems, is of course much more extensive, under cover of later rocks, than its areas of outcrops. As compared with all earlier systems since the Early Paleozoic, however, the Jurassic is the least extensively developed system on the continent.

Figure 162 shows the numerous areas of Late Jurassic plutonic rocks in western North America.

Description of the Rocks. *Pacific Coast.* The Jurassic strata of the Pacific Coast, from southern California to southwestern Alaska, are largely of marine origin. Various kinds of strata are represented, and these are often more or less metamorphosed, and much folded and faulted. Dark slates are perhaps the most common. The strata are nearly everywhere closely associated with igneous material, this being particularly true in British Columbia where the Jurassic system is unusually thick—8000 to 18,000 feet—and volcanic rocks constitute about one-half of it.

One of the best Jurassic sections is in the Taylorsville region of northeastern California where about 6000 feet of non-metamorphosed, marine strata and associated volcanic rocks have been subdivided into a number of formations as listed in the table on page 237 (Mariposa and Knoxville excepted).

In much of the Sierra Nevada of California, the Late Jurassic

Mariposa formation, consisting mainly of slates, with associated sandstone, conglomerate, and volcanic rocks, is widely developed and much folded (Fig. 155).

In the Coast Range of California there are two extensive formations —*Franciscan* and *Knoxville*—each partly or wholly of Late Jurassic age. The Franciscan consists of limestones, shales, sandstones, and conglomerates, with closely associated metamorphic and basic igneous rocks. The Knoxville is made up of well-bedded shales and sandstones, with

FIG. 156. Rainbow Natural Bridge near the middle-southern **boundary of Utah.** This great rock arch, over 300 feet high, has been carved out of red Jurassic sandstone. (Photo by H. E. Gregory, U. S. Geological Survey.)

some conglomerate beds. It reaches the tremendous thickness of fully 15,000 feet. It rests by unconformity upon the Franciscan formation. The Knoxville was formerly placed in the Lower Cretaceous by some geologists, and partly in the Upper Jurassic by others. Recently (1933) F. M. Anderson, after a careful study of many of its fossils, has definitely placed it in the Upper Jurassic. Both Franciscan and Knoxville are much folded and faulted in the California Coast Range.

The Jurassic rocks so extensively outcropping along both the southern and northern coastal regions of Alaska are much like those of California.

Tremendous bodies of granite (or rather "granodiorite") of Late Jurassic age occur throughout the Pacific Coast region from western Mexico well into Alaska (Fig. 162). These intrusions occurred at the

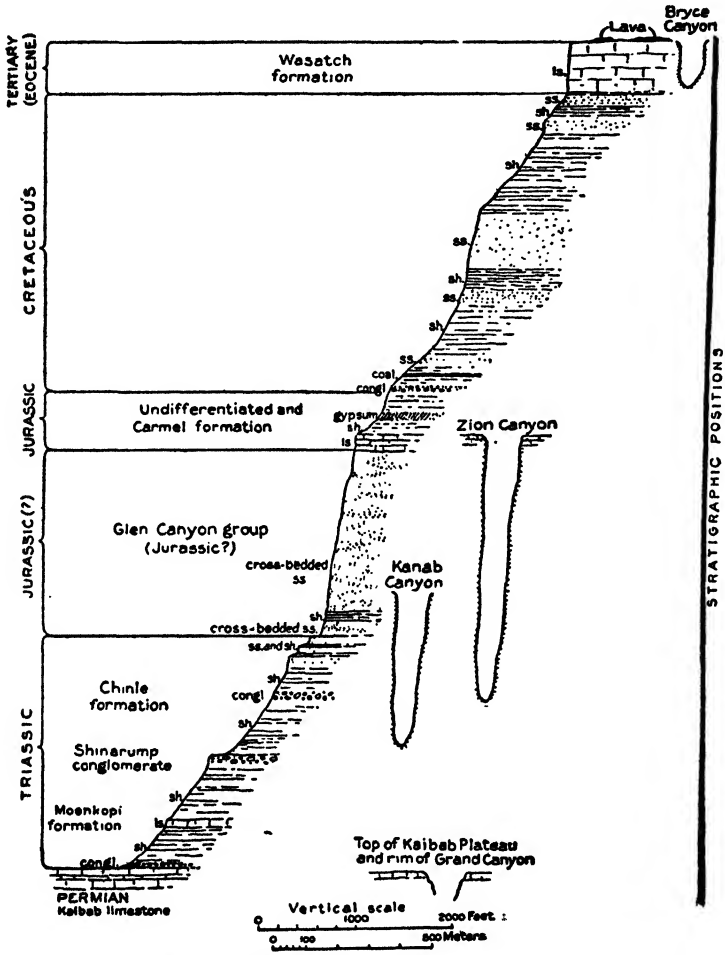


FIG. 157. Generalized columnar section showing the nature and relations of the rock systems from Late Permian to Early Tertiary in the Colorado Plateau. Note the stratigraphic positions of the Jurassic system, and of Grand, Kanab, Zion, and Bryce Canyons. (After H. E. Gregory, U. S. Geological Survey.)

time of the Sierra Nevada Revolution (see beyond). Granodiorite of this age is wonderfully exposed in the walls of Yosemite Valley, California, and elsewhere in the Yosemite National Park (Fig. 163).

Western Interior. In the western interior of the continent, Triassic and Jurassic strata often have not been satisfactorily separated, but extensive "Red Beds" (with gypsum) of continental origin, like those of the Triassic system of the region, are doubtless of Jurassic age. A good idea of the character and order of these rocks may be gained from the formations listed under the Colorado Plateau in the table on page 237. These formations reach a combined thickness of 2000 to 3000 feet. In the walls of Zion Canyon, Utah, continental formations of nearly horizontal, massive sandstone over 2000 feet thick are wonderfully exposed.

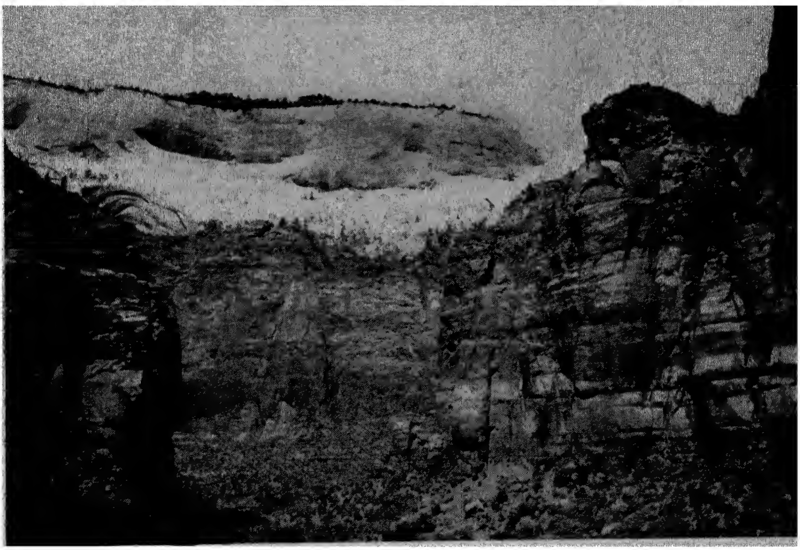


FIG. 158. Jurassic sandstone (red below and white above) over 2000 feet thick in the walls of Zion Canyon, Utah. Lowest portion is probably Triassic.

This sandstone is red in its lower portion, and white in its upper portion (Fig. 158). The lowest part of the section in Zion Canyon is probably of Triassic age.

The great Vermilion Cliff and the White Cliff, traceable for many miles, and forming such impressive features of the landscape in northern Arizona and southern Utah, consist of the red *Wingate* sandstone and the nearly white *Navajo* sandstone, respectively. The remarkably cross-bedded Navajo sandstone is probably of wind-blown origin.

The Rainbow Natural Bridge, probably the largest and most magnificent feature of its kind in the world, is carved out of red Jurassic sandstone.

The only known true, marine, Jurassic strata in the western interior are of Upper Jurassic age. These marine rocks, which comprise all types of ordinary sediments, especially limestones and shales, are usually highly folded or tilted in the Rocky Mountains, Wasatch Mountains, Black Hills, etc., and hence are there generally exposed only in narrow belts. The greatest thickness of these rocks in the western interior seems to be several thousand feet in southeastern Idaho and western Wyoming where they constitute the *Twin Creek* formation. Elsewhere the marine strata are seldom more than a few hundred feet thick. All of the

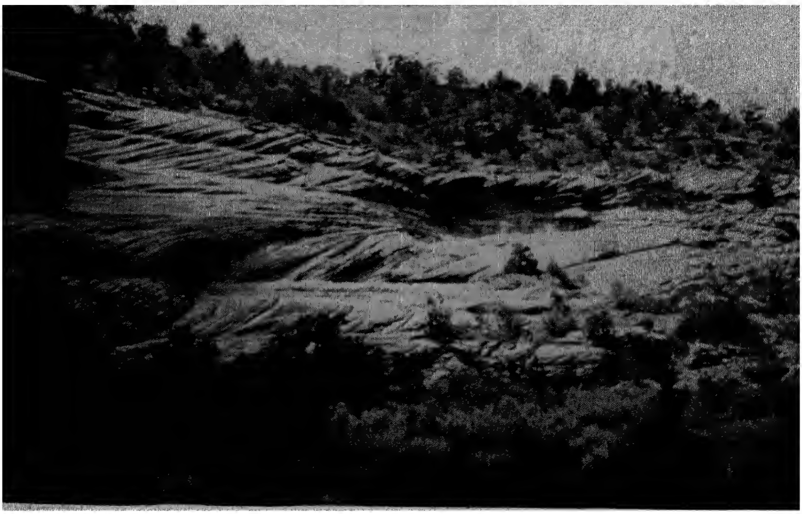


FIG. 159. An illustration of the remarkable cross-bedding of Jurassic sandstone in southern Utah and northern Arizona. Three miles north of Kanab, Utah.

Upper Jurassic marine strata of the western interior of the continent occur within the area represented as having been occupied by sea water on map, Fig. 161. Overlying the marine Jurassic in the western interior, there are several non-marine formations topped by the very Late Jurassic *Morrison* formation of continental origin and remarkable because so many remains of great reptiles have been found in it.

In the Colorado Plateau Jurassic strata have been relatively little disturbed by folding and faulting, but in the mountains of Colorado, northeastern Utah, Wyoming, and Montana they have usually been more or less strongly deformed, their upturned edges often outcropping along the flanks of the ranges.

Physical History

Pacific Coast. The Pacific Coast region of North America seems to have been above sea level in earliest Jurassic time. Then the waters encroached upon the land, covering the Pacific Coast region from the south end of Lower California to southwestern Alaska as shown by

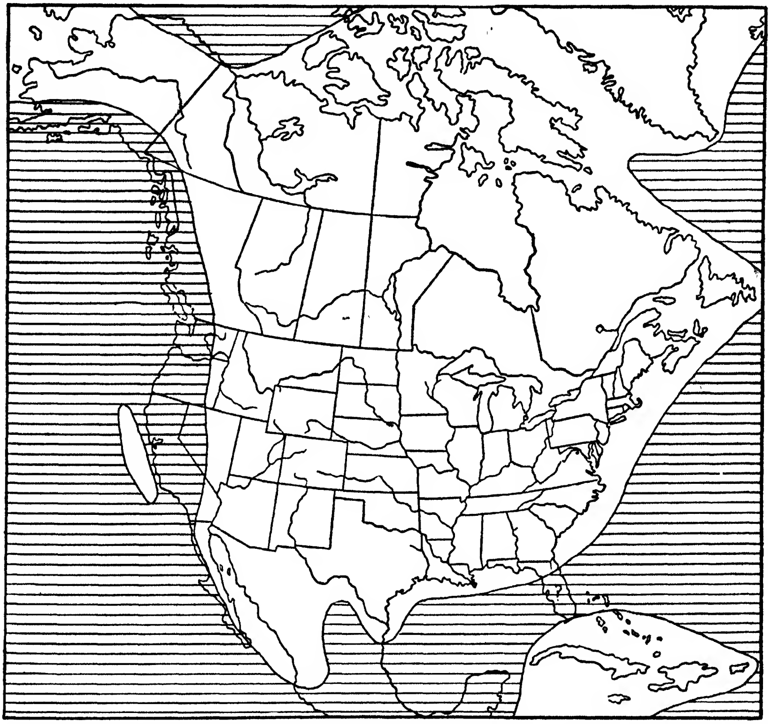


FIG. 160. Generalized paleogeographic map showing sea and land relations in North America during Early Jurassic time. White areas, land; ruled areas, sea. Principal data (modified) from maps by C. Crickmay and C. Schuchert.

Figure 160. The sites of the Sierra Nevada, Cascade, and Coast Ranges were then sea-covered. Barring relatively minor changes, the marine waters became more extended until they reached the climax for the period. This was in the early Late Jurassic time (Fig. 161). Still later a narrow seaway probably extended across northern Mexico and into southern California, connecting the Pacific and Gulf of Mexico.

As in the Triassic, tremendous volcanic activity, most of it submarine or on volcanic islands, occurred. "Toward the end of Lower (Early) Jurassic time volcanoes appeared along a great belt from southern Alaska, through the Coast Range region of British Columbia, and into California. Great beds of agglomerate and flows of lava piled upon

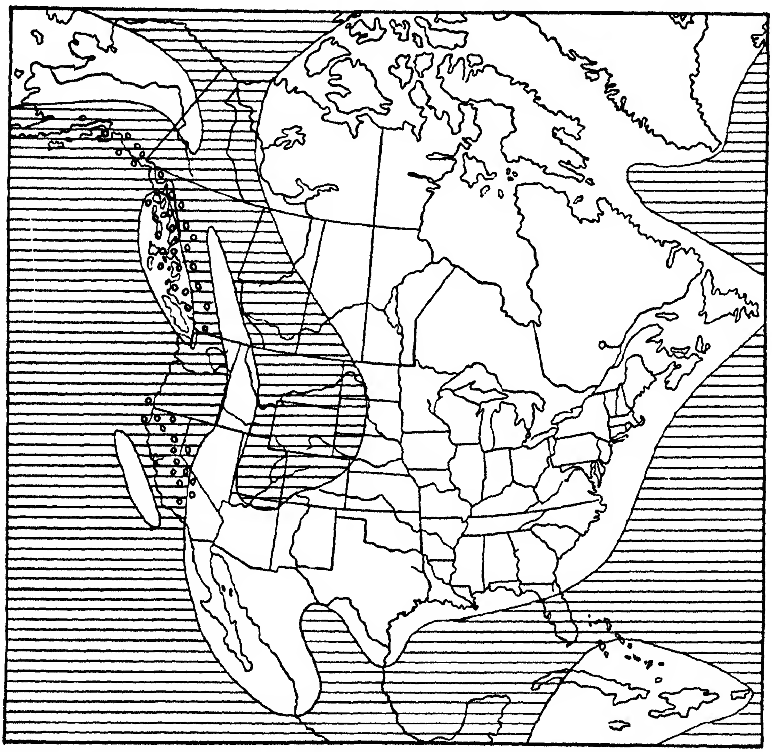


FIG. 161. Generalized paleogeographic map showing sea and land areas in North America during the early part of Late Jurassic time. White areas, land; ruled areas, sea. This was the greatest Jurassic sea. Small circles show the general distribution of Middle and Late Jurassic volcanoes. Principal data (modified) from maps by C. Crickmay and C. Schuchert.

each other on a sinking earth's surface. For one brief spell, in the early Middle Jurassic, the violent eruptions ceased, and during this interval the sea spread over most of the lava-devastated areas, and left marine deposits. But shortly these were again buried beneath the products of renewed eruptions until thousands of feet of lavas and pyroclastics had accumulated." (C. H. Crickmay.)

By the close of the period the sea had withdrawn from the whole Pacific Coast region.

Western Interior. During Early and Middle Jurassic times there was deposition of continental "Red Beds" material over much of the central portion of the western interior, especially in the states of Wyoming, Colorado, Utah, northern Arizona, and northern New Mexico. These rocks are excellently exposed in the Colorado Plateau where they are usually 2000 to 3000 feet in thickness. Some of the principal formations are listed in the preceding table. The remarkable cross-bedding of sandstone formations 2000 or more feet thick, such as the Navajo sandstone, strongly points to their wind-blown origin on a grand scale (Fig. 159).

An important change occurred in the Late Jurassic, namely, the spreading of a shallow sea southward from the Arctic Ocean to the east of Alaska and south to northern Arizona. This arm of the sea, or great mediterranean, was 600 miles wide in the western interior of the United States, and considerably narrower in Canada as shown on map, Fig. 161. Some of the principal marine formations are the *Sundance* and *Twin Creek* of the Wyoming region, and the *Carmel* formation in the Colorado Plateau, all of which are rich in fossiliferous limestone.

Well before the close of the period, the interior sea vanished, and renewed "Red Beds" deposition occurred. Among these continental formations are the Morrison and McElmo, each several hundred feet thick.

Eastern North America in the Jurassic. No Jurassic strata now occur in the eastern two-thirds of North America, and we have no evidence that any ever were deposited there, hence that vast area was dry land undergoing erosion during the whole period. The period was ushered in by a considerable upwarping of the Atlantic border accompanied by faulting and tilting, particularly of the Triassic (Newark) rocks, as shown in Fig. 147. That this uplift actually occurred, and that the Jurassic period in the eastern United States was a time of extensive erosion, is well established, because the whole Atlantic seaboard, including the tilted and faulted Triassic strata, was worn down toward the condition of a peneplain and the next sediments (Lower Cretaceous) were deposited upon the eastern portion of that worn-down surface. For instance, on Staten Island and in northern New Jersey, the Lower Cretaceous beds may be seen resting directly upon the deeply eroded Trias-

sic rocks, and hence the proof is conclusive that during much, if not all, of the Jurassic period active erosion was taking place, and this in turn implies that the Triassic beds were well elevated in the early Jurassic.

Close of the Jurassic (Sierra Nevada Revolution). The close of the period witnessed profound geographic changes in the western part

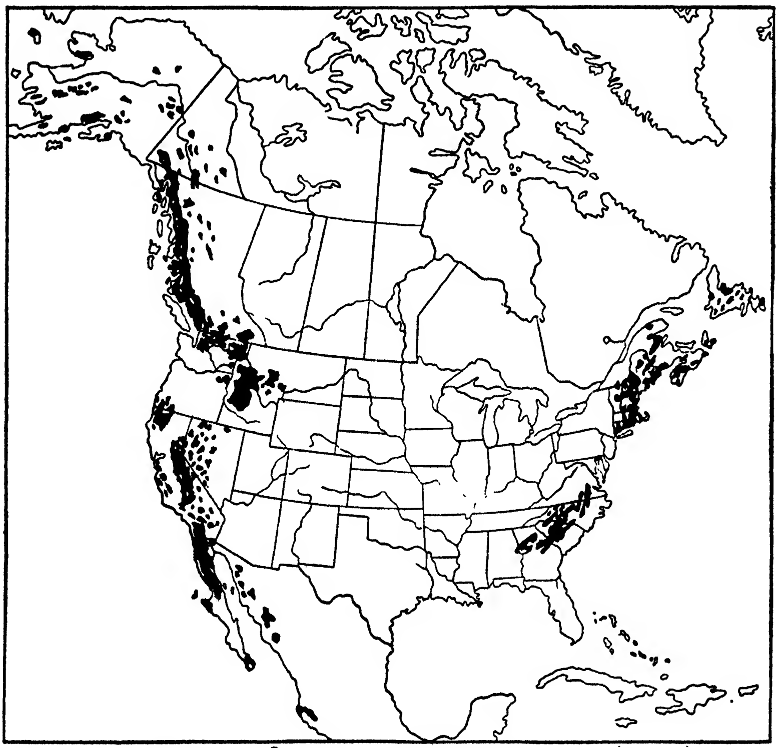


FIG. 162. Map of North America showing (in black) the principal outcropping Paleozoic and Mesozoic batholiths. Those of the west are nearly all of Late Jurassic age, and those of the east are Late Permian with more or less associated Devonian intrusive bodies in New England and northeastward.

of the continent. During both the Triassic and Jurassic periods, as well as throughout much of Paleozoic time, there had been more or less continuous deposition of sediments on the Pacific slope over the sites of the present Sierra Nevada, Cascade, and Coast Range Mountains. Late in the Jurassic these thick sediments, particularly in the Sierra Nevada region, were subjected to a tremendous force of lateral compression, the strata being upheaved, folded, and crumpled (Fig.

155). Thus the Sierra Nevada Mountains of California were borne out of the ocean and the Pacific shore line was transferred to the western base of the newly formed range. The climax of the orogeny came at or near the close of the period. The Sierra Nevada Mountains, in this their youth, were most likely a lofty range, higher, longer, and wider than today. They were later much worn down by erosion, after which

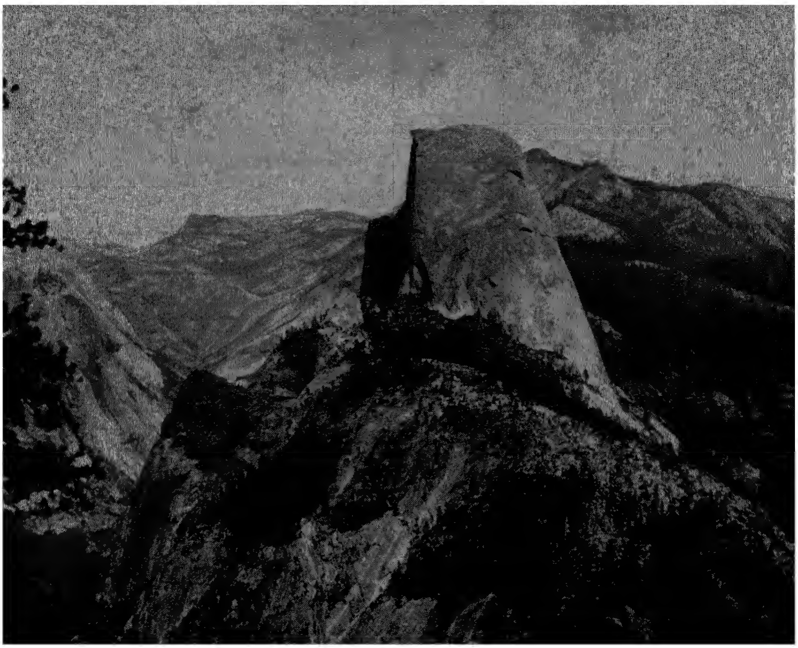


FIG. 163. Half Dome (altitude, 8852 feet) and part of the Sierra Nevada Range as seen from Glacier Point in Yosemite National Park. Practically all the rock in view is Late Jurassic granite (or granodiorite) forming part of the great Sierra Nevada batholith which was intruded at the time of the Sierra Nevada Revolution, and since laid bare by erosion. (Photo by F. E. Matthes, U. S. Geological Survey.)

they were raised to their present altitude by Late Cenozoic movements. Figure 166 shows several stages in the history of the range.

The best evidence indicates that this orogeny also more or less severely folded the strata of mountains in western Nevada; the mountains of southern California and northern Lower California; the Klamath Mountains of northwestern California; the Cascade Mountain region through Oregon and Washington; western Idaho; and western British Columbia.

It is perhaps not too much to say that the whole Pacific Coast of the United States, and probably most of the west coast of the continent, was more or less profoundly affected by the Sierra Nevada Revolution.

The strata occupying the site of the present Coast Ranges were somewhat deformed, but probably only enough to form a chain of islands or a very low mountain range. This is proved by the fact that Lower Cretaceous strata are found resting unconformably upon the deformed Jurassic rocks. The orogenic movements which produced the Coast Range Mountains as we now see them came later.

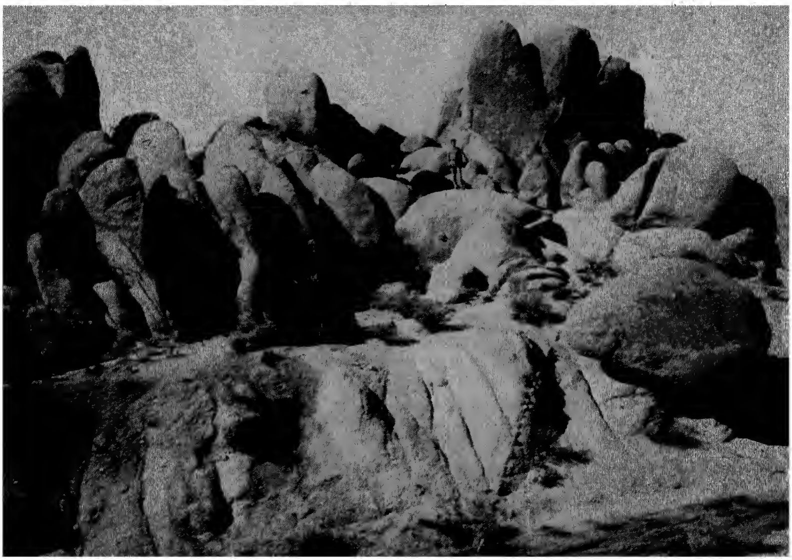


FIG. 164. Late Jurassic(?) jointed granite weathering under desert conditions in the Pinto Mountains, Riverside County, California.

The great arm of the sea or gulf which spread over the western interior region late in the Jurassic was drained as a result of these crustal disturbances. Hence we learn that all of North America was dry land at the close of the Jurassic period.

Accompanying the Sierra Nevada Revolution, tremendous volumes of granite (or granodiorite) magmas were intruded in the form of numerous large and small batholiths. This was the greatest time of plutonic igneous activity in the post-Proterozoic history of North America. These batholiths, now exposed to view because of profound subsequent erosion, occur throughout most of the Pacific Coast region from

western Mexico well into Alaska (Fig. 162). The Sierra Nevada batholith alone is about 400 miles long and 25 to 75 miles wide (Fig. 163), but the British Columbia batholith is very much larger.

These tremendous bodies of magma very largely rose into place during a late stage of the orogeny as indicated by the fact that the rock folds, involving Late Jurassic strata, are often cross-cut by the intrusives (Fig. 166A). Recent studies indicate that both the orogeny and the

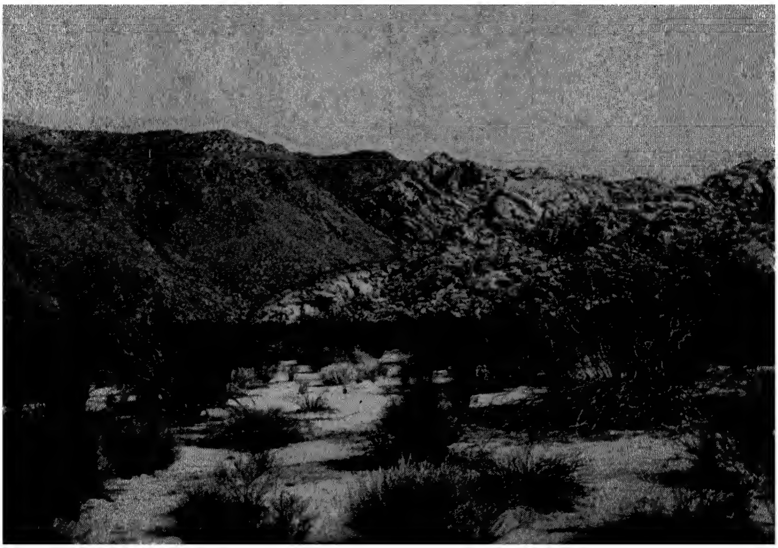


FIG. 165. Late Jurassic(?) granodiorite (lighter), on the right, showing a sharp intrusive contact against darker, much older (Archeozoic) (?) granite, on the left. Seven miles southwest of Twenty-nine Palms, California.

intrusions may have continued here and there well into Early Cretaceous time.

CLIMATE

In general the evidence from the character and distribution of the organisms shows that the climate of the world was somewhat cooler than usual during the Early Jurassic, as indicated by the curbing or dwarfing of various marine animals and land animals and plants. The climate of Middle and Late Jurassic times was, however, characterized by general mildness. Corals, for example, ranged much farther northward then than they do today, and great dinosaurian reptiles roamed regions as far north as Montana.

A study of migrations of certain animals shows that the Arctic Sea was cooler than the Atlantic and Pacific, but it is perhaps too much to say that the northern sea was then as cold as now. There was quite certainly some definition of climatic zones, especially in Late Jurassic time.

The "Red Beds" and great cross-bedded sandstone formations of the western interior of the United States indicate desert or semi-arid con-

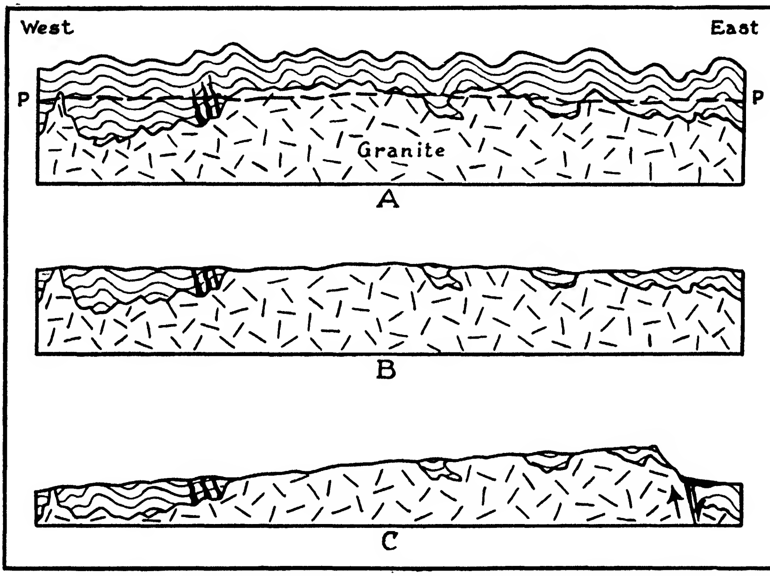


FIG. 166. Highly generalized structure sections across the Sierra Nevada Range in California, showing three stages in the history of the range. *A*, conditions as they were (barring erosion) just after the Late Jurassic folding, intrusion of the granite batholith, and filling of the gold-bearing "Mother Lode" veins (black streaks at middle left); *B*, conditions in Late Tertiary time after *A* was eroded to an old age surface (*PP*); and *C*, present day condition of the great tilted fault block, with the "Mother Lode" veins outcropping.

ditions when and where these rocks were deposited. Under dry-climate conditions, little of the iron of iron-bearing minerals is leached out of the sediments produced mainly by mechanical weathering and so a red color is caused by oxidation of iron compounds after deposition of the sediments in basins. Eddying and swirling desert winds only could have produced such grand and often curved cross-bedded structures.

Coal beds of Middle Jurassic age signify a mild, humid climate in various parts of the world (see below) during that time.

Economic Products

The great gold-bearing veins or lodes of the famous "Mother Lode Belt" of the Sierra Nevada occur in Jurassic and older slates. The deposits were formed by the filling of a prominent zone of fissures with quartz, gold, and other minerals carried upward by hot, magmatic solutions emanating from the Sierra Nevada batholith during its intrusion (Fig. 166A). Deposits of this kind were formed in many other places on the Pacific Coast at the same time. These lodes are the sources of most of the so-called "placer-gold" occurring in stream gravels.

In California, also, important quicksilver deposits occur in metamorphosed Jurassic and later rocks.

Coal beds of some importance are found, mostly in the Lower Jurassic, in central Europe, various parts of Asia, Alaska, Australia, and elsewhere.

The famous Solenhofen lithographic stone of Bavaria is of Jurassic age.

Foreign Jurassic

Europe. The marine transgression which, in Late Triassic time, resulted in the submergence of the great salt lakes and other basins of central and western Europe, continued into the Jurassic. Even in the early (Lias) part of the period the sea covered considerable areas in western, central, and southern portions of the continent. The strata are mostly typical shallow sea sediments, though some coal-forming swamps existed around the sea borders in central Europe. These Early Jurassic strata are usually conformable upon and not sharply separated from the underlying Triassic.

A progressive marine transgression continued through the middle of the period and well toward its close, extending farther and farther eastward, till much of the continent was submerged. This was one of the greatest marine transgressions in the known geological history of Europe. As would be expected, the strata of later Jurassic age contain much more limestone than those of the earlier part of the period, because of the more widespread clear water areas. During all this time the great series of oölites were forming in England and the famous Solenhofen lithographic limestone was being deposited in southern Germany.

Just before the close of the period a considerable retrogression of the sea set in, draining certain areas and leaving lakes or estuaries in certain other places.

Other Continents. Jurassic marine strata are known in many places in Arctic lands, thus showing extensive sea waters of that time there.

A great marine transgression also affected Asia, so that extensive areas of the continent became submerged, except mostly in the central portion. Widespread Jurassic deposits are known in Asia Minor, Siberia, India (especially the Himalayas), Persia, Turkestan, and Japan.

Jurassic rocks are also known in northern and eastern Africa, western South America, Australia, and New Zealand.

CHAPTER XXI

ROCKS AND PHYSICAL HISTORY OF THE CRETACEOUS

Origin of Name and Subdivisions

The term *Cretaceous,* from the Latin "Creta" for chalk, was given to the period because of the prominence of chalk beds in the rocks of this age, especially in England and France. In fact, one of the most striking features of the landscape in southern England and northern France consists in the frequent exposures of beds of white or very light colored chalk. Perhaps the most famous are the Dover Cliffs of England. In many parts of the world, however, the Cretaceous system is not rich in chalk deposits. In the United States, chalk is extensively developed in the Cretaceous of Alabama and Texas. The system was first carefully studied in England, but the names of the French subdivisions are now more widely employed in Europe. The Cretaceous system in North America is commonly divided into two parts—a Lower and an Upper—often separated by unconformity.

Following are the principal subdivisions of the Cretaceous system in six important parts of North America:

	N. Atlantic Coastal Plain	Alabama	Texas	Great Plains	S. Rockies—Colo. Plateau	California
UPPER CRETACEOUS	(Missing) Monmouth Matawan Magothy Raritan	(Missing) Ripley Selma Eutaw Tuscaloosa	(Missing) Navarro Taylor Austin Eagle Ford Woodbine	Lance—Laramie Montana Colorado Dakota	Price River Lewis Mesa Verde Mancos Dakota	Garzas Moreno Panoche Chico
LOWER CRETACEOUS	Potomac { Patapsco Arundel Patuxent	(Missing)	Washita Fredericks-burg Trinity (Missing)	Kootenai—Lakota (Missing)	(Missing)	Shasta { Horsetown Paskenta

Distribution and Description of the Rocks

General Distribution. The very great surface distribution of strata of known Cretaceous age is shown on the accompanying map (Fig.

167). Upper Cretaceous strata are much more widely developed and more extensively exposed at the surface than those of Lower Cretacous age. No system of strata, from the Cambrian to the present, is so extensively exposed as the Cretaceous. The Tertiary system, counting both volcanic and sedimentary rocks, is about as widely exposed.

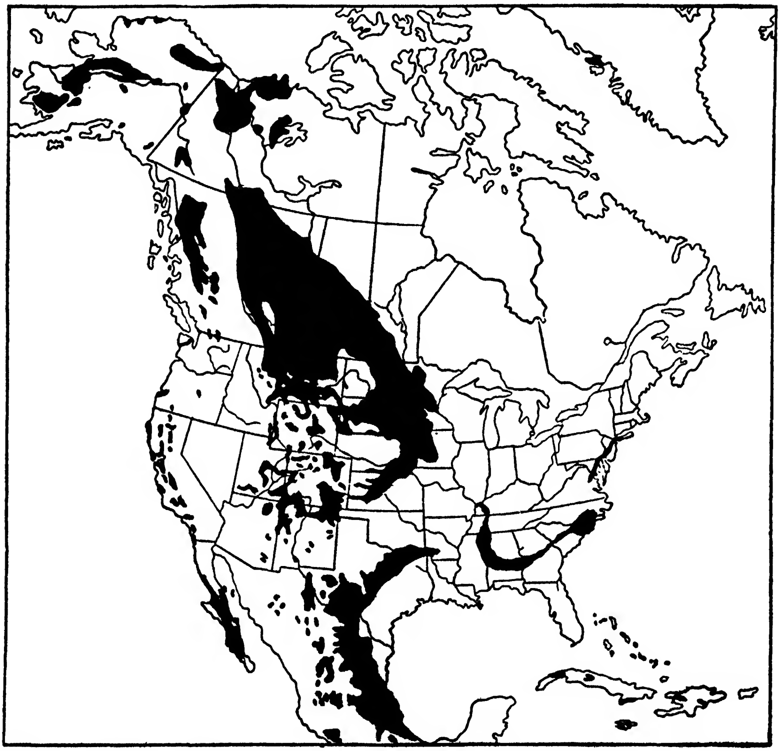


FIG. 167. Map of North America showing the surface distribution (areas of outcrops) of Cretaceous strata. The large and small areas in the western interior of the continent very largely represent Upper Cretaceous deposits.

Cretaceous strata form a narrow outcropping belt along the western side of the Atlantic Coastal Plain, with the exception of parts of Virginia and North Carolina where younger strata completely conceal the Cretaceous. Passing eastward from the exposed belt, well borings show that a large part of the whole Coastal Plain is underlain with Cretaceous strata. "The sediments in general form a series of thin sheets which are inclined seaward (Fig. 179), so that successively later formations are encountered in a journey from the inland border of the region

toward the coast." The northernmost Cretaceous exposures are on Martha's Vineyard, Massachusetts.

In a similar way, in the Gulf Coastal Plain (including Mexico) the widely outcropping Cretaceous strata (Fig. 167), dipping gently toward the coast, are known to be extensively developed under cover of later formations. In general, therefore, the actual extent of Cretaceous strata in the Atlantic and Gulf Coastal Plains is much greater than its surface exposures.

A large part of the western interior of North America shows Upper Cretaceous strata at the surface, but there are only a few small areas of Lower Cretaceous. The very extensively developed Upper Cretaceous strata east of the Rocky Mountains, in both the United States and Canada, form a very large outcropping area (Fig. 167), first, because they have been little deformed by folding or faulting, and, second, because they have usually not been much covered by later material. Within the Rocky Mountains, however, the Cretaceous strata (very largely Upper Cretaceous), because of more or less folding and subsequent deep erosion, show a patchy areal distribution. In the Colorado Plateau the rather widely exposed and comparatively little deformed Cretaceous strata have been much cut into by erosion. Large and small bodies of Cretaceous are concealed under later rocks in many parts of the western interior of the continent.

On the Pacific Coast of the United States, relatively small areas of outcrops of both Lower and Upper Cretaceous sediments show, but, because the rocks are there usually in a highly deformed condition, they are really much more extensive than the surface areas. The Cretaceous system is most remarkably developed in California.

Cretaceous rocks are widely exposed in Mexico (including Lower California), western British Columbia, western Yukon Territory, and Alaska in all of which there is often a patchy distribution which has resulted from much erosion of the more or less deformed rocks.

Description of the Rocks. *Atlantic Coastal Plain.* Three well-known Lower Cretaceous formations of the Atlantic Coast have been called the *Potomac* series. These are listed in the table on page 253. They are all of continental origin. They consist mainly of sands and clays with a total thickness of about 725 feet. The sands are often cross-bedded, and some of the clays are highly colored. Fossil plants are common, and in some places there are beds of lignite. Several small unconformities occur within the *Potomac* series.

The Upper Cretaceous deposits rest unconformably upon the Lower Cretaceous. They are largely marine. The Upper Cretaceous formations of New Jersey are typical of the North Atlantic Coastal Plain. They consist mainly of clays, sands, gravels, and greensand (glauconitic) marls with a total thickness of about 1000 feet. There are some associated lignitic beds. These Upper Cretaceous deposits have been subdivided into a number of formations separated by minor unconformities. Some of the best known of these formations are listed in the table on page 253.

The Atlantic Coastal Plain strata show almost no folding or faulting, but, as already stated, they dip gently seaward, mostly under cover of later formations.

Eastern Gulf Coastal Plain. The Alabama Cretaceous is typical of this region in which the Lower Cretaceous seems to be entirely missing. The Upper Cretaceous of Alabama, according to Stephenson, comprises four formations with a total thickness of fully 2600 feet. These formations are listed in the table on page 253. They constitute a variable assemblage of strata including sands, glauconitic sands, gravels, thin-bedded clays, white chalk, soft limestones, and marls. These beds are seldom more than slightly consolidated. Special mention may be made of the *Selma* formation consisting mostly of soft chalky material very rich in microscopic shells, some of them foraminiferal, and strikingly white. It is hundreds of feet thick (Fig. 173).

The Cretaceous system of the eastern Gulf Coastal Plain, like that of the Atlantic Coastal Plain, is very little deformed, and it dips gently seaward largely under cover of later formations.

From the above descriptions, the Atlantic and eastern Gulf Coastal Plain Cretaceous deposits are seen to be largely unconsolidated. They are only slightly tilted sediments. The Lower Cretaceous strata are largely non-marine, while the Upper Cretaceous are largely marine.

Texas and Mexico. The Cretaceous system is excellently developed in Texas, only the very oldest and youngest beds being absent. It outcrops in a wide belt extending not only across Texas, but also across southeastern Oklahoma and into southwestern Arkansas. The Lower Cretaceous there consists of three formations as listed in the table on page 253. Together these formations are called the *Comanche* series. The series reaches a maximum thickness of about 7500 feet. All but the lowest part is of marine origin. Common kinds of sediments such as sands, marls, clays, marly clays, soft limestones, and chalky limestones constitute the great bulk of the formations. They are usually rich in

fossils. Special mention may be made of the very extensive *Fredericksburg* formation of Texas which is almost entirely a marine, chalky limestone from 1000 to 5000 feet thick.

Lower Cretaceous strata, thousands of feet thick and much like those of Texas, are very widespread in Mexico excepting its northwestern part (including Lower California).

In Texas four formations, together known as the *Gulf* series, comprise the Upper Cretaceous (see table on page 253). These are also very largely of marine origin. Their total thickness is more than 2000 feet. Sands, clays, marls, limestones, and chalk constitute the great bulk of the strata. One formation (*Austin*), several hundred feet thick, is largely an impure chalk. Various beds of fragmental volcanic material are associated with the Late Cretaceous strata of Texas.

Upper Cretaceous strata, thousands of feet thick and much like those of Texas, are very extensively exposed in the eastern one-half of Mexico and in Lower California.

Cretaceous strata (Fig. 167) and Cenozoic volcanic rocks (Fig. 231) are by far the most extensively developed surface rocks in Mexico.

In the Coastal Plain parts of both Texas and Mexico, the Cretaceous beds are almost unaffected by folding, but they are considerably faulted, especially in the Balcones fault zone across Texas. The Coastal Plain beds do, however, dip gently toward the Gulf. Farther west, in the mountains of Texas and Mexico (including Lower California), the Cretaceous system is more or less deformed.

Great Plains. In the Great Plains region, mostly just east of the main axis of the Rocky Mountains from Colorado northward, there occur certain formations—*Lakota, Kootenai,* etc.—which consist mostly of shales, sandstones, and much coal. They are Lower Cretaceous deposits of continental origin. Earliest Cretaceous strata are missing.

The very extensive Upper Cretaceous strata of the Great Plains of the United States have been divided into a number of important formations (see table on page 253). Earliest of these is the *Dakota* formation which is chiefly sandstone, mostly of non-marine origin, and several hundred feet thick. It is easily recognizable over many thousands of square miles, often forming escarpments and hogbacks because of its resistance to erosion. Next above the Dakota are two largely marine formations (*Colorado* and *Montana*) consisting of shales, sandstones, limestones, chalk, and some continental beds including coal. Thicknesses range to more than 8000 feet. The *Laramie* formation is quite certainly

mostly of non-marine origin, comprising both fresh-water and land deposits (including much coal). The formation shows a variable thickness possibly up to several thousand feet. The *Lance* formation, in part marine and in part continental in origin, attains a thickness of 700 feet in North Dakota. It is at least in part an eastern marine phase of the Laramie. Beds of volcanic ash occur in the Upper Cretaceous in various parts of the Great Plains.

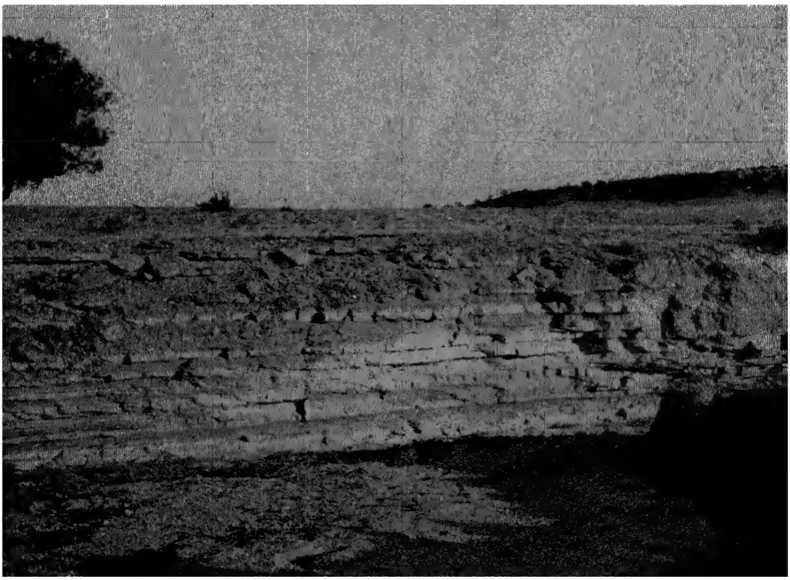


Fig. 168. Early Upper Cretaceous marine beds of limestone and shale which were laid down in the great interior sea. Near Thatcher, Colorado. (Photo by N. H. Darton, U. S. Geological Survey.)

The Cretaceous of the vast Great Plains area, extending far north into Canada, is much like that of the United States just described, but it has been less studied.

The Great Plains Cretaceous beds have a very wide, gentle synclinal structure with upturned edges around the Black Hills and along the base of the Rocky Mountains (Fig. 169).

Rocky Mountains and Colorado Plateau. Upper Cretaceous rocks are prominently developed in the Rocky Mountains of the United States and in the Colorado Plateau. The Lower Cretaceous, however, is only sparingly represented. Important subdivisions of the Upper Cretaceous are listed in the table on page 253. They consist largely of well-bedded

shales and sandstones, mainly marine in the lower part and non-marine in the upper part. They generally range in thickness from a few thousand feet to 20,000 feet (in Wyoming). Volcanic materials are found in various parts of the Upper Cretaceous in the Rocky Mountains. There are also some plutonic rocks, probably of late Cretaceous age.

In the Rocky Mountains the Cretaceous strata are usually more or less folded, varying from nearly horizontal (Fig. 170) to highly disturbed. Their upturned edges often flank the mountain ranges.

The Cretaceous strata in the Colorado Plateau, in common with Paleozoic and older Mesozoic strata, are comparatively little deformed by folding or faulting.

Pacific Coast. The thickest and most impressive development of the Cretaceous system in North America, if not in the world, is on the Pacific Coast, particularly in western California.

In the Coast Range of California, the Lower Cretaceous (or *Shasta* series) comprises the *Paskenta* and *Horsetown* formations. The Paskenta is made up of shales and sandstones, with some conglomerate and limestone beds, thousands of feet thick. It rests unconformably upon Late Jurassic (Knoxville) strata, and it is overlain by the Horsetown formation of sandstones and shales thousands of feet thick.

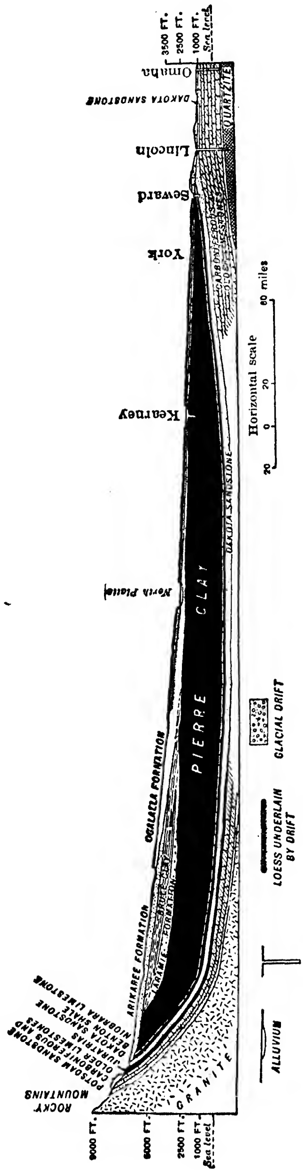


FIG. 169. Structure section across Nebraska from the Rocky Mountains to Omaha. The Dakota, Benton, Niobrara and Pierre formations are Cretaceous. (After Darton, U. S. Geological Survey, Prof. Paper 17.)

Lower Cretaceous strata, usually folded and sometimes metamorphosed,

are also widely developed in western British Columbia and Alaska, with some coal in both regions.

The Upper Cretaceous is also prominently developed on the Pacific Coast. The great *Chico* formation, reaching a thickness of 5000 to 10,000 feet, is finely exposed in the coastal mountains from the southern part of Lower California to Alaska. It consists mostly of sandstones, shales, and conglomerates. Overlying the Chico in California are three

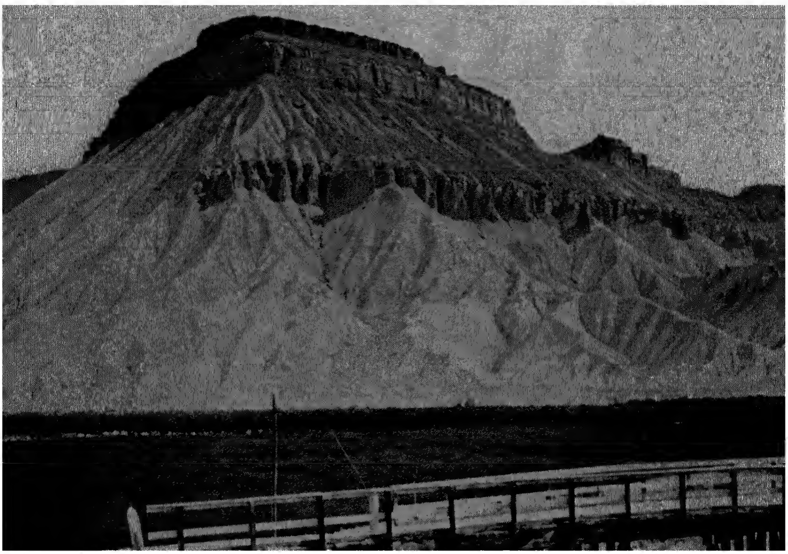


FIG. 170. Nearly horizontal beds of Upper Cretaceous age in the western interior of the United States. The cliff-forming beds are resistant sandstones, and soft shales form the intricately sculptured slopes. Little Book Cliffs near Palisade, Colorado. (Photo by U. S. Reclamation Service.)

formations (see table on page 253) also totaling many thousands of feet in thickness.

The marine Cretaceous of California is most remarkable for its great aggregate thickness. Some of the sandstone and shale formations are many thousands of feet thick. If all the maximum thicknesses of the different Cretaceous formations of California are combined, the total is nearly 90,000 feet. This is a truly amazing figure, but it should of course be understood that no single section in any region shows such a thickness. In many places, however, thicknesses of 10,000 to 20,000 feet are common, and 40,000 to 50,000 feet of Cretaceous strata are said to occur in the Coalinga (California) district alone. The

fact that the enormously thick Cretaceous beds of California are very largely clastic sediments proves that subsidence of the sea floor must have occurred where the deposition was taking place.

The Pacific Coast Cretaceous strata are generally much folded and often faulted, and so the areas of outcrops only partly show their real extent.

Physical History

General Statement. Cretaceous time was in general characterized by a gradual encroachment of the sea upon the continent, reaching a

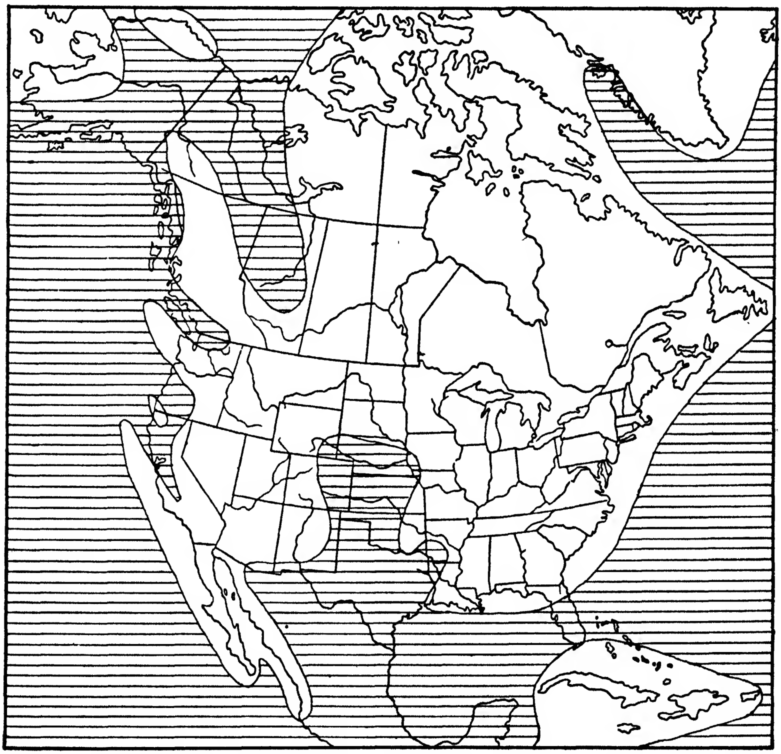


Fig. 171. Generalized paleogeographic map showing sea and land areas in North America during the later part of Early Cretaceous time. White areas, land; ruled areas, sea. Principal data (modified) from maps by B. Willis and C. Schuchert.

grand climax in the earlier part of Late Cretaceous time, and then gradually waning to disappearance.

Soon after the opening of the period the sea spread over eastern

Mexico and part of Texas; northwestern California; southwestern British Columbia; southern Alaska; and the Mackenzie River Basin. These embayments became larger until, in late Early Cretaceous time, the seas were about as shown by Figure 171. The waters continued to spread so that, in the earlier part of Late Cretaceous (Colorado) time, the conditions were about as shown by Figure 172. At that time North

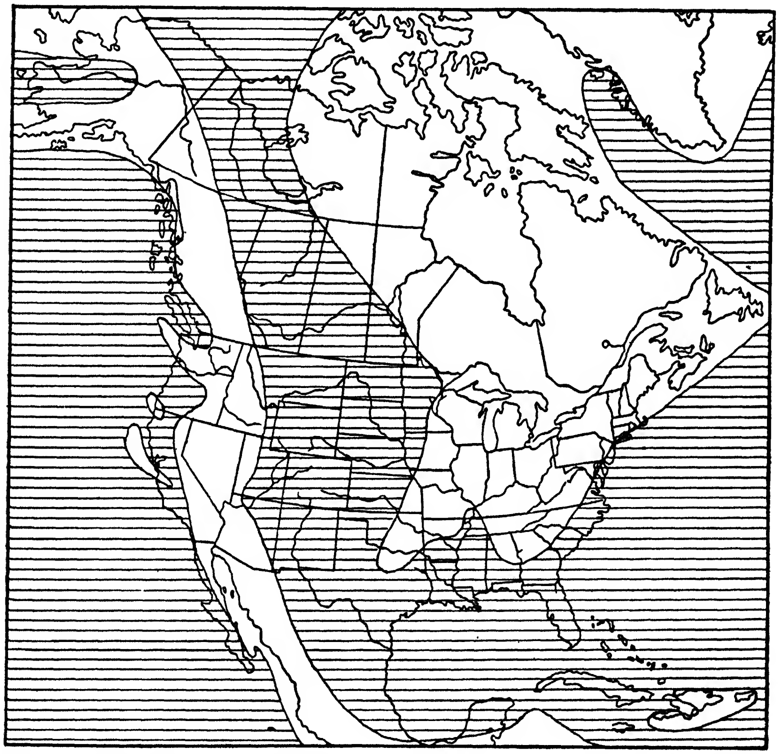


FIG. 172. Generalized paleogeographic map showing sea and land relations in North America during the earlier part of Late Cretaceous time. This was the greatest Mesozoic sea. According to D. W. Johnson, the sea also covered the northern Appalachian region. White areas, land; ruled areas, sea. Principal data (modified) from maps by B. Willis and C. Schuchert.

America was cut in two by a vast sea connecting the Gulf of Mexico with the Arctic Ocean. This was the greatest of all Mesozoic or Cenozoic epeiric seas, and it was the last time that marine conditions ever prevailed well within the interior of the continent. The sea then gradually became smaller, leaving all land at the end of the period.

Atlantic and Eastern Gulf Coasts. The Cretaceous period opened with the coast line of the eastern United States somewhat farther out than it now is, but, early in the period, there was enough subsidence, or possibly warping, of the coastal lands to allow deposition of sediments over much of what is now known as the Atlantic Coastal Plain. That but little downwarping of the surface was necessary in order to produce proper conditions for this sedimentation is evident, because the coastal lands just prior to the Cretaceous were already low-lying as a result of the long Jurassic erosional interval. There was just enough warping of the low coastal lands to produce wide flats, flood plains, shallow lakes, and marshes back from the real coast line. Over such areas were deposited the sediments derived from the Piedmont Plateau and Appalachian areas. The very irregular arrangement of the deposits (Potomac) and their rich content of fossil land plants afford conclusive evidence that the sediments were deposited under continental conditions.

The rather widespread unconformity between the Lower and Upper Cretaceous in the Atlantic area proves that, at the close of the Early Cretaceous, there must have been enough emergence of the lands to convert the basins of deposition into areas of erosion. Early in the Late Cretaceous, however, a submergence of the coastal lands took place, inaugurating the deposition of the Upper Cretaceous strata. The general character, mostly marine [1] origin, and present extent of these deposits prove that the submergence allowed a shallow sea to spread over much of what is now called the Atlantic and eastern Gulf Coastal Plain.[2] The white chalk of the Selma formation in Alabama was deposited this time (Fig. 173). According to D. W. Johnson, the Late Cretaceous sea also spread westward over most of the northern Appalachian region, which he believes was already peneplaned, but if so, all deposits laid down in that sea have been removed by erosion.

It is very important to note that *Appalachia,* the great land-mass which had persisted through the many millions of years of the Paleozoic era as well as most of the Mesozoic era, largely disappeared under the Cretaceous sea not again to appear in anything like its former magnitude.

Texas and Mexico. During most of Early Cretaceous time a clear and unusually deep epicontinental sea occupied much of Mexico and Texas and immediately adjoining regions. Great limestone beds were

[1] Some beds of continental origin occur in the Upper Cretaceous of Maryland and New Jersey.

[2] Certain minor oscillations of level are here disregarded.

formed in this usually clear sea. Perhaps the maximum northward extension of this sea took place during late Early Cretaceous (Washita) time, when marine waters probably reached as far northward as Nebraska (Fig. 171).

Throughout Late Cretaceous time marine waters appear to have persisted over the Texas area, having been particularly clear during the deposition of the Austin chalk. Most of Mexico was also submerged.

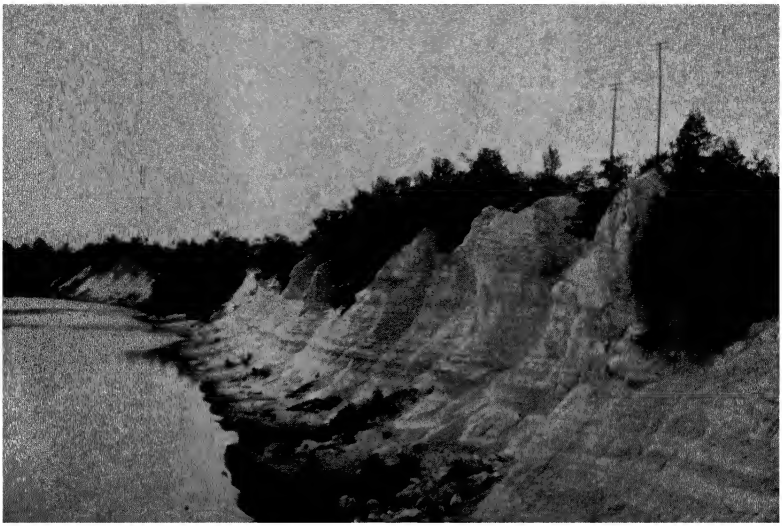


FIG. 173. Typical exposure of Upper Cretaceous (Selma) chalk in Alabama. (After L. W. Stephenson, U. S. Geological Survey, Prof. Paper 81.)

The finding of various volcanic necks and beds of volcanic fragmental material in direct association with Upper Cretaceous strata in Texas, mainly along the so-called "Balcones fault," shows that there was considerable vulcanism there during Late Cretaceous time.

Rocky Mountain-Great Plains Region. The best evidence seems to show that there was limited deposition in this vast area during very Early Cretaceous time, and perhaps none at all (except in the Mackenzie River Basin) during the first half of that time. In the second half of the Early Cretaceous, deposits of continental origin (Kootenai and Dakota), very much like those of the Potomac series on the Atlantic Coast, were laid down in the middle part of the Great Plains area, that is, in the northern United States and southern Canada. At this same

time an arm of the Arctic spread south to central Alberta and an arm of the Gulf of Mexico spread north into Nebraska (Fig. 171).

Early in Late Cretaceous time, the Rocky Mountain-Great Plains region was the scene of a very extensive marine transgression beginning after Dakota time, and reaching a maximum during the Colorado epoch (Fig. 172). In the comparatively clear waters of this sea there were laid down chalky limestones and other deposits. This great marine invasion was one of the most extensive in the known history of the continent. The sea spread from the Gulf of Mexico northward over the Rocky Mountain-Great Plains region to the Arctic Ocean by way of the Mackenzie River Basin. There is no evidence that this vast interior sea had any connection with the Pacific Ocean (Fig. 172). In the middle of Late Cretaceous time, the connection with the Arctic was cut off, and the much narrower sea reached only as far north as northern Alberta. Near the close of the Cretaceous all that remained was a very narrow arm of the sea extending from the Gulf sea in western Texas northward into North Dakota. At the close of the period even this remnant of the great interior sea vanished.

At various times and places during the Late Cretaceous, there was more or less volcanic activity (largely explosive) in the Rocky Mountain-Great Plains region of the United States as proved by the beds of tuff, agglomerate, etc., interbedded with the Upper Cretaceous strata.

Pacific Coast. Very early in the Cretaceous, small embayments of the Pacific Ocean reached into northwestern California, southwestern Oregon, southwestern British Columbia, southern Alaska, and northern Lower California. In later Early Cretaceous time the Lower California embayment was gone, but the others were so enlarged that much of the coastal region from central California to southern Alaska was sea-covered as shown by Figure 171.

In the early part of Late Cretaceous time, the conditions were about as shown by Figure 172. Southern Alaska was then land, but the sea swept over one-half of California and much of Lower California. Still later the Pacific Coast seas waned to disappearance by the close of the period.

Remarkable physical conditions must have obtained in western California, especially in the north, to have given rise to such a phenomenal thickness (50,000 ± feet) of sediments during Late Jurassic and Cretaceous times. Apparently the explanation is not far to seek because the newly uplifted lofty Sierra Nevada Mountains must have undergone

vigorous erosion with resulting rapid deposition of great quantities of clastic sediments in the marine waters which then occupied the sites of the Great Valley and northern Coast Range of California. An unconformity, indicating more or less uplift, deformation, and erosion, usually separates the Lower and Upper Cretaceous in California and Lower California. This shows that deposition of the great pile of Cretaceous strata was not an unbroken process.

In British Columbia and Alaska, the presence of coal beds proves that large swampy areas, with prolific plant growths, must have existed locally during some of Cretaceous time.

Close of the Period in the West (Rocky Mountain Revolution). The close of the Cretaceous period, or, what is the same thing, the close of the Mesozoic era, was marked by one of the most profound and widespread disturbances in the post-Proterozoic history of North America.

Over the Rocky Mountain district there had been more or less deposition of sediments (both marine and continental) during Proterozoic, Paleozoic, and Mesozoic times. Toward the close of the Cretaceous, there was vigorous deformation, including both folding and dislocations of the strata, not only throughout the Rocky Mountain district in North America from the Arctic Ocean to Central America, but also even along the line of the Andes Mountains to Cape Horn—altogether more than one-fourth of the way around the earth. This great crustal disturbance has been called the "Rocky Mountain (or Laramide) Revolution." While the folding was usually not as intense as at the time of the "Appalachian Revolution," nevertheless there were very considerable uplifts accompanied by more or less folding of the strata in many parts of the district (Figs. 174, 175).

The portion of the Rocky Mountains situated in the northern United States and southern Canada suffered the severest deformation, where strata 50,000 to 76,000 feet thick were folded and faulted into a mountain range probably no less than 20,000 feet high. Referring to this region Schuchert says that "there had been no orogeny from early Proterozoic time until the close of the Cretaceous. During this vast time there was laid down in this area about 20,000 feet of Mesozoic strata resting upon 26,000 feet of Paleozoic formations, and these in turn lie (almost) conformably upon about 30,000 feet of but little metamorphosed Proterozoic rocks. It is the longest accessible geological section known anywhere and attests to the striking fact that

the earth's crust may subside at least 14 miles before it becomes folded into mountains."[1]

In Wyoming (e.g. Big Horn Mountains) and Colorado (e.g. Front Range), a number of great, elongate, domelike anticlines, with cores of pre-Cambrian granite, were formed.

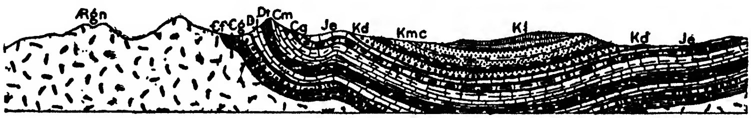


FIG. 174. Structure section in the Rocky Mountains of western Montana showing moderate folding of Cretaceous and older rocks. *Argn,* Archean; *Cg, Cf,* Cambrian; *Dt, Dj,* Devonian; *Cq, Cm,* Carboniferous; *Kl, Kmc, Kd,* Cretaceous. (After Peale, U. S. Geological Survey, Folio 24.)

The Rocky Mountain orogeny began well before the close of the Cretaceous, and it continued with more or less intensity into the Early Tertiary, but it reached a general climax near the close of the Cretaceous.

Instead of folds, or following the folding, great thrust faults were often developed. A fine example is in Glacier National Park where Proterozoic rocks were pushed at least 10 or 12 miles over Cretaceous

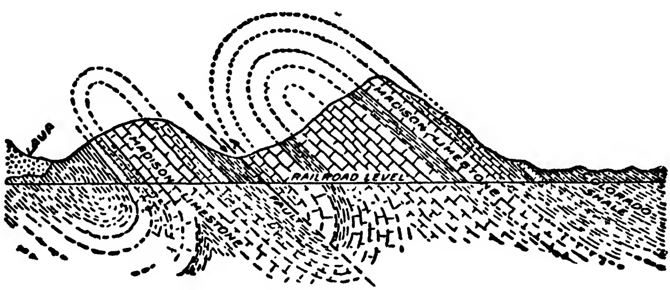


FIG. 175. Structure section in the Rocky Mountains of southwestern Montana showing highly folded Cretaceous and older rocks. After the development of the two overturned folds, the rocks broke along the fault, and the mass on the right was shoved partly over upon the mass on the left. (After U. S. Geological Survey.)

rocks on the so-called Lewis thrust fault (Figs. 176, 177). The pile of gently folded Proterozoic rocks (largely strata) involved in the great overthrust block, covers many hundreds of square miles, and reaches a thickness of fully two miles. Because of frictional drag of the over-

[1] C. Schuchert: *Geol. Soc. Amer. Bul.,* Vol. 34, 1923, p. 191.

riding block, the underlying, weak Cretaceous strata were usually much folded (Fig. 178). Much of the movement along this profound fault probably continued into the Early Tertiary.

The Rocky Mountain orogeny was also pronounced in parts of Mexico, as for example in the Parras region in the north-central part of the country where very thick Cretaceous and older strata were severely folded and thrust faulted.

Fig. 176. Diagrammatic structure section showing how the great body of Proterozoic strata has been thrust-faulted from the west for miles over upon Late Mesozoic strata in Glacier National Park, Montana. The Mesozoic beds were folded by action of the over-riding block. Length of section, about 25 miles. Vertical scale, much exaggerated.

Considerable igneous activity accompanied the Rocky Mountain Revolution. Volcanoes were active, and laccoliths and small batholiths were emplaced, here and there in the Rocky Mountain region from north-central Mexico to British Columbia during Late Cretaceous-Early Tertiary time.

The original Rocky Mountains were greatly subdued by erosion by Middle Cenozoic time, and their existing altitude and main relief features are results of still later movements and erosion.

The Eastern Highland Region in Late Cretaceous Time. Turning our attention to the eastern highland region of the continent, we find that significant changes took place there also. This region includes the whole present-day area extending from central Alabama through the Appalachian-Piedmont district, New York, New England, and to the Gulf of St. Lawrence. This region was above the sea and subjected to profound erosion during most of the Mesozoic era so that, by Middle Cretaceous time, it was worn down to a condition varying from early old age to a peneplain.

The most perfect peneplanation was in the northern Appalachian area, extending from southern New York through Pennsylvania and the Vir-

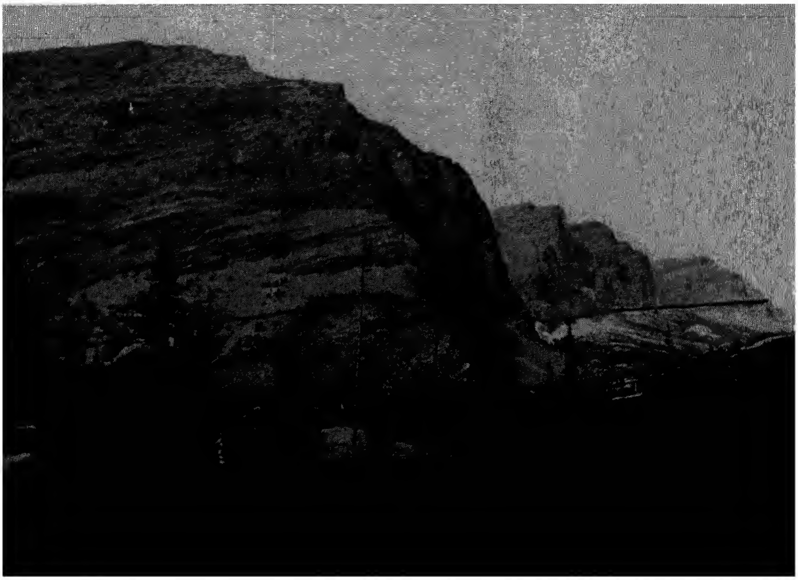


FIG. 177. The Lewis thrust fault (indicated by the black line) visible for 4 miles in the north wall of lower Swiftcurrent Canyon in Glacier National Park, Montana. The great pile of Proterozoic strata, 3000 feet thick above the fault, has been thrust-faulted to the right (eastward) over upon the Cretaceous strata (under the fault), the latter having been more or less deformed by the over-riding action.

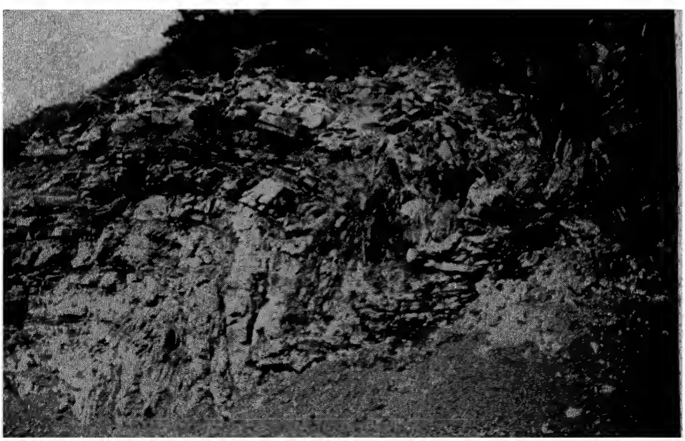


FIG. 178. A detail view of Cretaceous strata (shale and sandstone) crumpled by the over-riding action of the great fault block of Proterozoic rocks five miles north of Glacier Park, Montana.

ginias, where relatively weak and resistant strata alike were so thoroughly cut down that no masses projected prominently above a low-lying plain. This part of the old erosion surface has been called the Fall Zone peneplain (Fig. 179A). Farther northward, however, over northern New

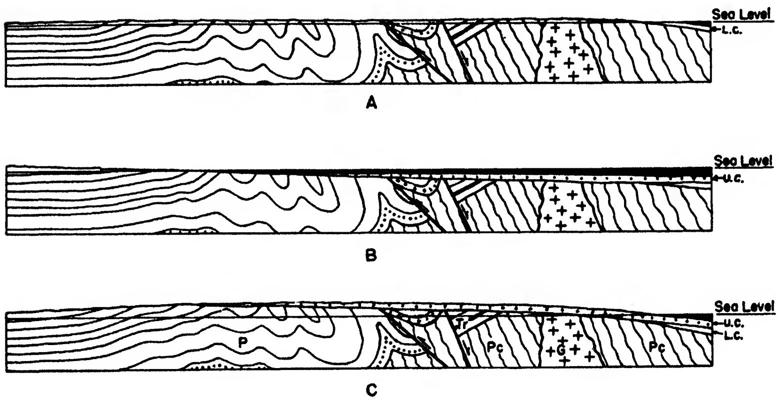


FIG. 179. Highly generalized structure sections across the Eastern Highland (Appalachian) region, from the Chesapeake Bay vicinity to southwestern Pennsylvania, showing the later Cretaceous history according to D. W. Johnson's theory. Pc = pre-Cambrian metamorphic rocks; G = pre-Cambrian intrusive; P = Paleozoic strata; Tr = Triassic rocks; L.C. = Lower Cretaceous non-marine strata; U.C. = Upper Cretaceous marine strata.

Section A, Middle Cretaceous Fall Zone peneplain with Lower Cretaceous non-marine strata on the right.

Section B, the widespread Late Cretaceous sea (in black) and strata (dotted).

Section C, upwarped region, largely mantled with Upper Cretaceous sediments, as it appeared at the close of the Cretaceous when a new cycle of erosion began and brought about superimposition of southeastward-flowing streams such as the Susquehanna and Potomac Rivers. Figure 250 illustrates the Cenozoic history of the same region.

York and northwestern New England, and also farther southward as in North Carolina, erosion reached the early old age stage rather than that of a peneplain because large masses of very resistant plutonic and metamorphic rocks there withstood the erosion more effectively.

According to D. W. Johnson, most of the Fall Zone peneplain became submerged under the Late Cretaceous sea in which a mantle of sediments was deposited on the peneplain surface (Fig. 179B).

The Cretaceous period was closed in the eastern highland region by a disturbance which produced an upwarp of the whole region extending

from central Alabama to the Gulf of St. Lawrence. This upward movement was unaccompanied by any renewed real folding of the rocks, the effect having been to produce a long, relatively narrow, irregular upwarp with its flanks dipping southeastward and northwestward, and with one end plunging gently toward the Gulf of St. Lawrence and the other toward the Gulf of Mexico. Uplifts of 1000 to 3000 feet were common throughout much of the region. The upward movement expelled the Late Cretaceous sea from the northern Appalachian area and there left the mantle of Late Cretaceous sediments extending over most of the arch (Fig. 179C). The uplift also caused retreat of the sea from the Atlantic Coastal Plain region, and this explains the widespread unconformity there between the Cretaceous and Early Tertiary strata.

Many streams flowed down the flanks or slopes of the great upwarp, first cutting channels through the mantle of alluvial and marine deposits in Early Tertiary time, and then into the underlying rocks, thus causing them to become superimposed streams. The discussion of this matter is continued in Chapter XXIV.

Climate

The temperature of North America in Early Cretaceous time was generally somewhat below normal, probably because the continent stood higher than usual, particularly in the west where high, wide mountains, formed at the time of the Sierra Nevada Revolution, were still in their prime. Similar lower temperatures were prevalent in many other parts of the world as shown by the distribution of plants and animal fossils. Glaciers existed in eastern Australia.

As would be expected, because of the unusually extensive epeiric seas, the climate of Late Cretaceous time seems to have been generally mild, with some distinction of climatic zones. The fossil evidence (e.g. Late Cretaceous plants in Greenland) indicates mildness of climate even within the Arctic circle.

The general temperature again dropped at the close of the Cretaceous because of the great mountains formed at the time of the Rocky Mountain Revolution.

Economic Products

Coal beds of moderate extent and value are known in the Lower Cretaceous rocks of Alaska, British Columbia, Australia, and Germany.

Coal is extensively developed in the Upper Cretaceous of the Rocky Mountain region of the United States. It is estimated that fully 100,000 square miles are underlain with chiefly lignitic and bituminous coals as well as a little anthracite coal. Important producers of Cretaceous coal are Colorado, Utah, Wyoming, Montana, and New Mexico. Considerable Cretaceous coal also occurs in Australia and New Zealand.

Sands used in foundry operations occur in the Atlantic Coastal Plain, especially in New Jersey.

Cretaceous clays of the Coastal Plains are used in the manufacture of brick and pottery.

A heavy production of petroleum and gas has been obtained from the Cretaceous strata of Texas, Louisiana, and Mexico. Both oil and gas are obtained from the Cretaceous in New Mexico, Wyoming, Colorado, Montana, and Alberta.

Cretaceous limestones are quarried in Kansas, Nebraska, and Iowa for building stone.

The most important sulphur deposits in the United States occur in rocks of Cretaceous age in Louisiana.

The vast supply of underground water obtained from the Cretaceous (Dakota) sandstone in the Great Plains region is worthy of special mention. Much artesian water is also derived from Cretaceous beds in the Atlantic and Gulf Coastal Plains. In the regions just mentioned the water is held under pressure in porous sandstone by overlying impervious clay or shale.

The copper deposits of the Butte, Montana, region are directly associated with the Late Cretaceous-Early Tertiary batholiths.

Foreign Cretaceous

Europe. Toward the close of the Jurassic and about the beginning of the Cretaceous, continental deposits were forming in parts of central and western Europe. Often these deposits grade from the Jurassic into the earliest Cretaceous. The Alpine region continued to be submerged under sea water. Soon after the beginning of the Cretaceous, a more or less interrupted marine transgression caused considerable areas of western and central Europe to become submerged, the deposits including both marine and non-marine beds. At the same time marine waters were more extended over the southern part of the continent. In western and central Europe all types of common sedimentary rocks were formed, as well as some beds of coal in Germany. As would be expected, be-

cause of the more prevalent marine conditions in southern Europe, limestone was more commonly formed there. The conditions just described continued essentially till the close of the Lower Cretaceous, when only comparatively slight sea retrogressions took place, as proved by the fact that the Upper Cretaceous rocks usually rest conformably upon the Lower Cretaceous. Thus in Europe there is not such a sharp break between the Lower and Upper Cretaceous as in North America.

As in North America, so in Europe, Upper Cretaceous time was marked by a great transgression of the sea. This marine invasion, which started in the Lower Cretaceous, continued with only slight interruptions well into the Upper Cretaceous, when much of Europe, except Scandinavia and northern Russia, was submerged. As in the Lower Cretaceous, the most common rock to form in southern Europe was limestone. In central-western Europe all types of ordinary sediments are represented, but, as already stated, in northern France and southern England, the Cretaceous contains much chalk (e.g. Dover Cliffs) which is made up of foraminiferal shells and which implies clear, if not fairly deep, sea water for its accumulation. Considerable greensand also occurs in the European Upper Cretaceous.

Toward the close of the period (Danian time) there were upward movements sufficient to increase the land areas and establish basins of non-marine sedimentation from Spain to and across the Alpine region as shown by the Cretaceous fresh-water deposits there.

Other Continents. Rather extensive areas of Cretaceous occur in New Zealand and Australia, where the rocks are frequently coal bearing and an unconformity often separates the Lower and Upper portions of the system.

Southwestern Asia, India (in the Himalayas), China, Japan, and Siberia all show more or less extensive development of Cretaceous strata. The Himalayan region was affected by considerable orogenic disturbances during later Cretaceous time. A feature of special importance in India was the inauguration, late in the period, of one of the greatest times of vulcanism since the pre-Cambrian and quite comparable to that of western North America already referred to. This is known as the Deccan lava region where some 200,000 square miles are covered by lava flows whose aggregate thickness reaches thousands of feet. This vulcanism continued into Tertiary time.

Over northern Africa extensive areas of marine Cretaceous rocks show much of that region to have been submerged during the period.

In South Africa Cretaceous rocks (especially the Lower) are considerably developed.

In South America Cretaceous rocks are widely distributed, especially in Brazil, where a notable marine invasion occurred in the Upper Cretaceous, though in places only continental deposits were formed. East of the Andes the Lower Cretaceous rocks are mostly non-marine. High in the eastern Andes and in southern Patagonia marine Upper Cretaceous strata are known. Toward the close of the period came the great orogenic disturbance, accompanied by much volcanic activity, in the Andes Mountains district.

CHAPTER XXII

MESOZOIC LIFE

THE physical revolution which closed the Paleozoic era was accompanied by one of the most profound changes in organisms in the earth's history, and hence we find the life of the Mesozoic to have been very notably different from that of preceding time. Some types of animals and various types of plants continued from the late Paleozoic, but the general aspect of Mesozoic life was distinctly more modern than that of the Paleozoic. In spite of this comparatively rapid evolutionary change in both fauna and flora, enough connecting links are known to make sure that the Mesozoic animals and plants were derived from the Paleozoic.

PLANTS

Seedless Plants. *Thallophytes* were well represented during Mesozoic time, the lime-secreting *seaweeds* being especially common.

Filicales (*ferns*) continued to be important.

Arthrophytes (*"horsetail rushes"*) were common and varied. Except for their greater size they were much like existing forms.

Lepidophytes (*"club mosses"*) were greatly reduced even in Early Mesozoic time. The few lingering *sigillarians* disappeared with the Triassic, and the once important *lepidodendrons* were reduced to a very subordinate position much like those of today.

Gymnosperms. These seed-bearing, non-flowering plants dominated the plant world of the Mesozoic era until Late Cretaceous time just as the higher seedless plants dominated the Middle and Late Paleozoic plants. The important *pteridosperms* and *cordaites* became extinct in the Triassic.

Ginkgos (*"maidenhair trees"*), including various species, were common and widespread. One species of the ginkgo has survived to the present day. Among living trees, it is probably the world's most ancient species. The ginkgo evolved from cordaites or a closely related form in Late Paleozoic time.

Cycads and *conifers,* which began in the Permian, were common and widespread in Mesozoic time. Both bore primitive types of flowers.

The *Cycads* were palmlike in appearance, but they were lower order forms than the palms and distantly related to them. The short, stout trunks of the cycads were (and are) crowned with clusters of long, palmlike fronds (Fig. 180). They attained their zenith of development in the Jurassic, and their modified descendants still exist in parts

FIG. 180. Jurassic cycad leaves. (After Ward, U. S. Geological Survey, Monograph 48.)

of the world. Some of the fossil cycads found in Mesozoic strata show a wonderful preservation of detailed structures of the plants. Not only because the cycads of Mesozoic (especially Triassic and Jurassic) time were so profuse in numbers and in variety of species, but also because they were remarkably widespread over the earth, the Mesozoic era has sometimes been called the "Age of Cycads." Cycads varied much in size from small palmlike forms to trees 40 to 60 feet high and several

feet in diameter. From the standpoint of evolution, it is important to note that much evidence leads to the conclusion that the earlier Mesozoic cycads were the progenitors of the highest of all classes of plants—the angiosperms. The conifers, in marked contrast to this history, have not given rise to any higher group of plants.

The *conifers*, including pines, sequoias and many other types of evergreen trees, gradually became more varied, and more and more modern in aspect during Mesozoic time. *Sequoias,* represented by the present-day "Redwoods" and "Big trees" of California, began in Late Jurassic time, and they were varied and widespread in the Cretaceous.

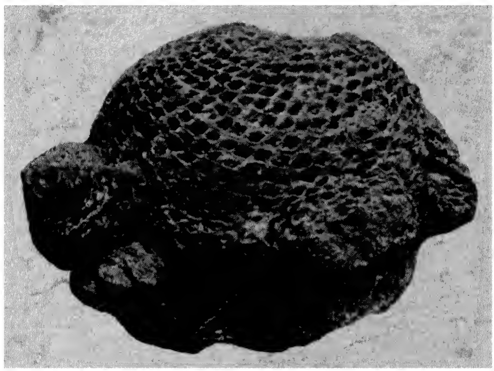


FIG. 181. A fossil cycad tree trunk, *Cycadeoidea pulcherrima*. This is a Lower Cretaceous species. (After Darton and W. S. Smith, U. S. Geological Survey, Folio 108.)

In various regions such as North Carolina, Virginia, and Arizona, trunks of fossil conifers reach diameters of 6 to 8 feet and lengths of 120 to 150 feet.

The remarkably preserved petrified trees, found in such abundance and beauty of color in the Triassic strata of the Petrified Forest of Arizona, represent mainly conifers which grew to heights of fully 150 feet. The petrified tree-trunks lie in prostrate positions in a sandstone-conglomerate formation which rests upon soft shales. The trunks, stripped of limbs, were stream-transported from a distance along with the coarse sediments in which they were embedded. More sediments were piled upon the trunk-bearing formation. When buried, the tree trunks were petrified, that is, replaced with silica carried by circulating subsurface water. As weathering and erosion proceed, the silicified logs gradually become uncovered and break into sections which move

down the slopes to lower levels where, because of the great resistance to the weather, they accumulate (Figs. 184, 185).

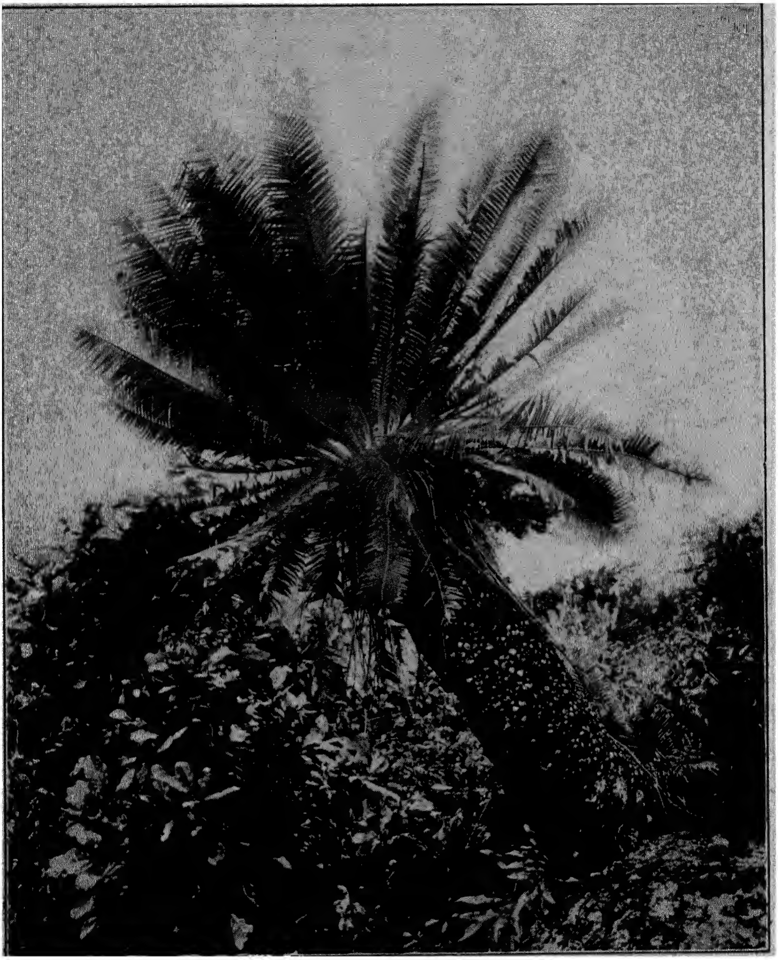


FIG. 182. A living cycad, *Dioon edule,* of Mexico. (From a photograph by Prof. C. J. Chamberlain.)

Angiosperms. These seed-bearing, true flowering plants constitute probably nine-tenths of the land plants of the present time. Just when they started is not known from the fossil record, but a few forms, with features strongly suggestive of primitive angiosperms, have been found in Jurassic strata. The fact that insects, such as bees and

butterflies, are known from the Jurassic strongly supports the conclusion that true flowering plants were in existence at the same time.

Although typical *angiosperms* are not definitely known to have existed before the Cretaceous, there can be no possible doubt about their presence (both monocotyledons and dicotyledons) in later Early Cretaceous time. By the close of the period the angiosperms had developed so phenomenally as to attain a position of supremacy among plants—

FIG. 183. Parts of a Triassic conifer, *Voltzia heterophylla*. (After Fraas from Scott's "Geology," courtesy of The Macmillan Company.)

a position which they have held ever since. The comparatively sudden appearance and remarkable development of the angiosperms "was one of the most important and far-reaching biologic events the world has known. . . . So far as we know, this flora appears to have had its origin in eastern or northeastern North America, in the Patapsco division of the Potomac series. Although the great majority of the plants found in association in these beds, both as regards species and individuals, still belonged to lower Mesozoic types, such as ferns, cycads, and conifers, we find ancient if not really ancestral angiosperms. . . . No

sooner were they (angiosperms) fairly introduced than they multiplied with astonishing rapidity and in the . . . Raritan they had become

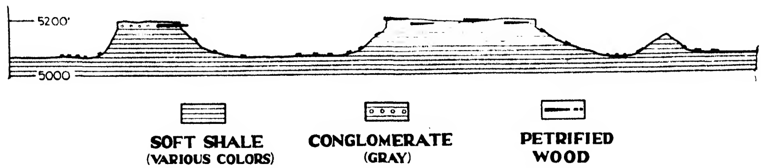


FIG. 184. A generalized structure section showing the mode of occurrence of petrified tree trunks in a conglomerate formation, and how, in weathering out, they break into sections which shift to lower levels. Petrified Forest of Arizona.

dominant, the ferns and cycads having mostly disappeared and the conifers having taken a subordinate position" (Knowlton). No present-day species existed, but, among the more modern genera were oaks, elms,

FIG. 185. Sections of petrified tree trunks weathered out of Triassic strata in the Petrified Forest of Arizona. (Photo by G. P. Merrill, U. S. National Museum.)

magnolias, maples, figs, laurels, palms, grasses, etc. Later Cretaceous angiosperms were remarkably uniform and widespread over the earth.

Invertebrate Animals

Lower Invertebrates. Among the tiny single-celled animals (*protozoans*), the foraminifers were exceedingly profuse during parts of Cretaceous time in clear sea waters which extended over the Gulf Coastal Plain area of the United States, southern England, much of

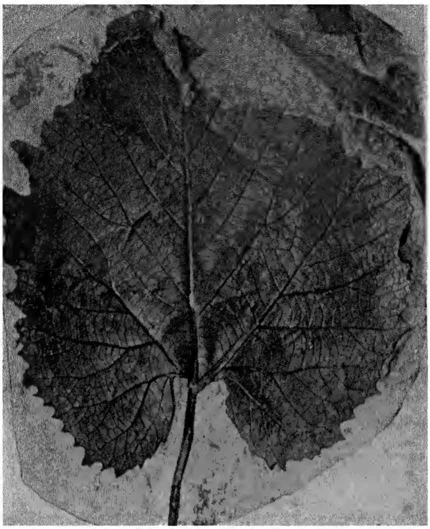


FIG. 186. Impression of a Late Cretaceous angiosperm leaf, *Vitis dakotana,* on a piece of shale from South Dakota. Width of leaf, seven inches. (After E. W. Berry.)

France, and other areas (Fig. 187). Their shells helped to build formations of chalk hundreds of feet thick and many miles in extent.

Sponges were very abundant and diversified. They are often beautifully preserved, even to the minutest details.

The modern types of *corals,* with six or eight partitions, began very late in the Paleozoic, and they were abundant and diversified throughout the Mesozoic. Like present-day corals they were tiny individuals, secreting carbonate of lime from sea water, and they nearly all grew in profusely branching colonies. The characteristic Paleozoic corals (with four partitions) became extinct in early Mesozoic time.

Echinoderms underwent no really profound evolutionary change during the Mesozoic. All important subdivisions were well represented. The stalked forms ("stone lilies") took on a more modern aspect, and

they were especially profuse and diversified during Jurassic time when single individuals are known to have had more than 600,000 segments made of carbonate of lime (Fig. 188). *Asterozoans* were moderately represented and they had already assumed a distinctly modern structure. *Echinoids* (sea urchins), which first attained much prominence in the Triassic, continued to increase in abundance and variety in the Mesozoic.

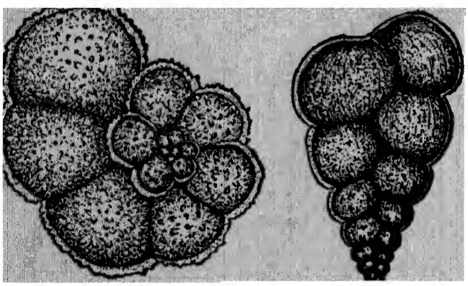


FIG. 187. Cretaceous foraminifers, greatly enlarged. (After Calvin, from Le Conte's "Geology," permission of D. Appleton and Company.)

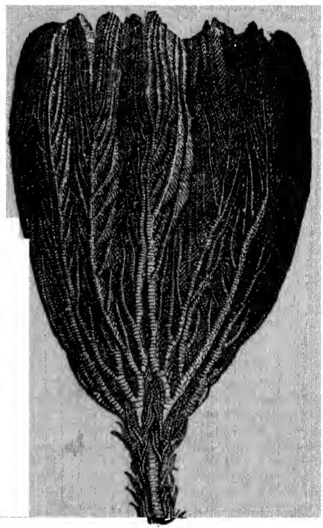


FIG. 188. A Jurassic crinoid, *Pentacrinus fossilis.* (After Goldfuss.)

Early in the Jurassic regular forms only existed, but later in the period the irregular forms made their first appearance. The regular forms were radially symmetrical, while the irregular ones were only bilaterally symmetrical (see Figs. 189, 190). Since the latter are distinctly more modern in structure, we have here another good illustration of progressive evolution toward modern forms. Both regular and irregular forms existed in the Cretaceous.

Brachiopods showed two important changes, namely (1) a great reduction in number of species and of individuals, and (2) the shells with straight-hinge lines becoming subordinate to those with curved-hinge lines for the first time, the latter having been very similar to the Early Tertiary genus illustrated by Fig. 191. To the present day the brachiopods never again became conspicuous elements of the fauna. In spite

of the important changes, a few of the Paleozoic genera survived the transition to the Mesozoic.

Mollusks. *Pelecypods* were more abundant and varied than ever before, their shells often constituting whole beds or thick strata. They were mostly modern in appearance and included many still existing genera. Thus the *oyster* family, represented by the living genus *Ostrea,* ranged through the Mesozoic, the common genera *Exogyra* and *Gryphea* lived during Jurassic-Cretaceous times, and the genus *Inoceramus* was important in the Cretaceous. Figure 192 shows several typical Mesozoic pelecypods.

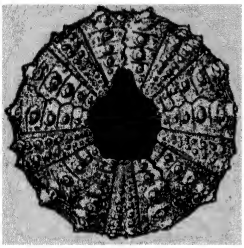


FIG. 189. A regular or radially symmetrical echinoid, *Pseudodiadema texanum,* of early Cretaceous age. (After Hill and Vaughan, U. S. Geological Survey, Folio 76.)

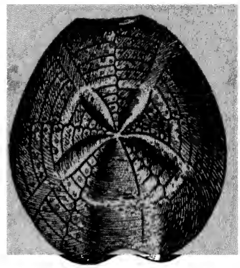


FIG. 190. An irregular or bilaterally symmetrical echinoid, *Hemiaster texanus,* of Cretaceous age. (After Hill and Vaughan, U. S. Geological Survey, Folio 76.)

Gastropods were common. Several Paleozoic genera continued into the Early Mesozoic, but more modern forms, including various existing genera, gradually appeared during the era.

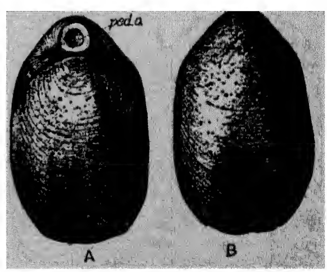
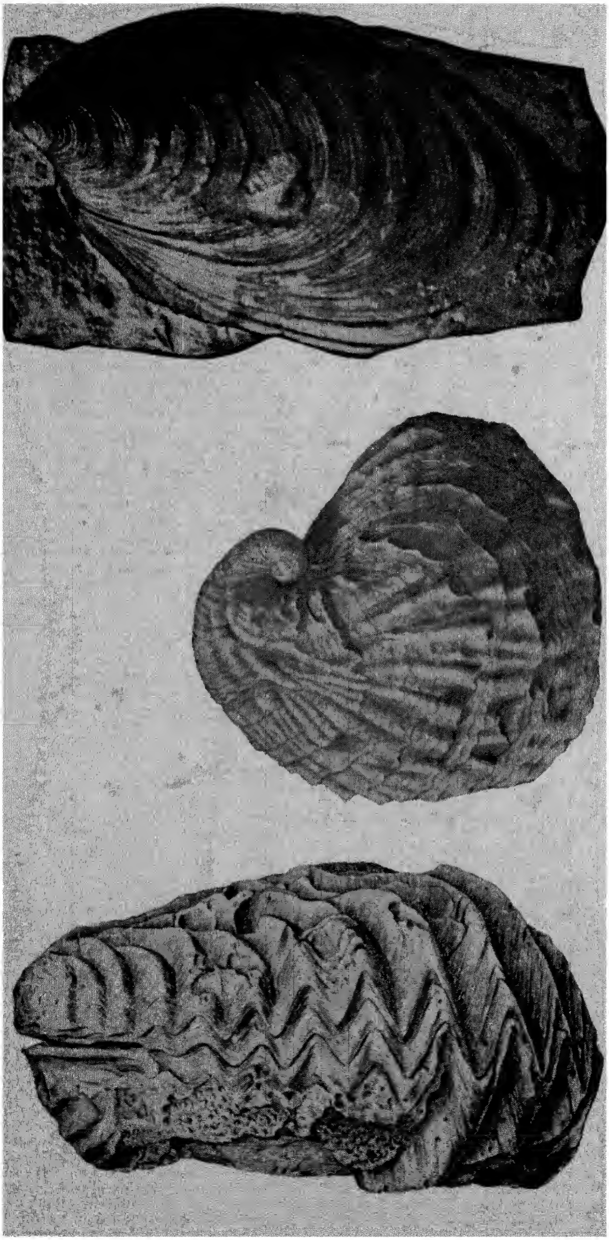


FIG. 191. An Eocene brachiopod, *Terebratula harlani.* Note the curved hinge line. (From Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company.)

Among the *cephalopods,* the straight-shelled *nautiloids,* which ranged through the Paleozoic era, became extinct in the Triassic, but the coiled forms then were still common and much like those of the Late Paleozoic. Late in the Mesozoic, however, the nautiloids were greatly reduced to a comparatively few coiled forms much like the modern pearly nautilus.



a b c

FIG. 192. Typical Cretaceous pelecypods: *a, Ostrea travisana* (Hill and Vaughan); *b, Exogyra ponderosa* (L. W. Stephenson); *c, Inoceramus labiatus* (Darton). (All from U. S. Geological Survey.)

Among the *ammonoids* an evolutionary feature of particular interest was the development of still greater complexity of shell structure. Goniatite-like forms still persisted, but, even early in the Triassic, forms with slightly serrated sutures or partition structures (e.g. *Ceratites*, Fig. 193) appeared. Later in the Triassic representatives of the most complex of all known chambered cephalopods, that is the *ammonites*, appeared. They reached their zenith of development in the Jurassic.

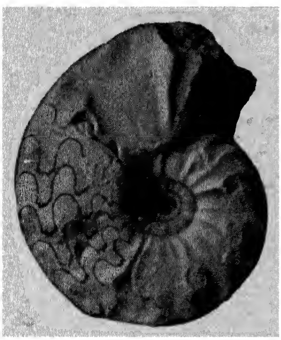


FIG. 193. A Triassic ceratite, *Ceratites trojanus*, with part of shell removed to show suture structure. (After J. P. Smith, slightly modified by accentuation of sutures.)

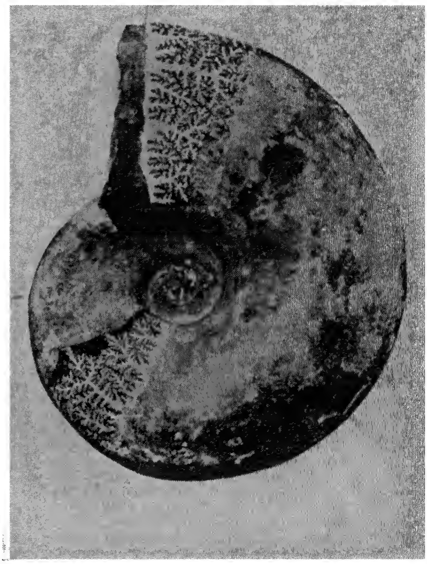


FIG. 194. A Cretaceous ammonite with part of outer shell removed to show the complicated suture or partition structure. Diameter of specimen, about 19 inches. (After Anderson and Hanna.)

In many of the coiled forms the compartment partitions became so highly complicated as to be comparable to the sutures of human skull plates (Fig. 194). Several thousand species are known from Jurassic and Cretaceous strata which, in certain localities, are literally filled with their fossil remains. Not only were they the most complex cephalopods of all time, but also many of them were of great size. Some of the coils were several feet in diameter, and would have been 30 to 40 feet long if straightened out.

During later Mesozoic time many of the ammonites showed a re-

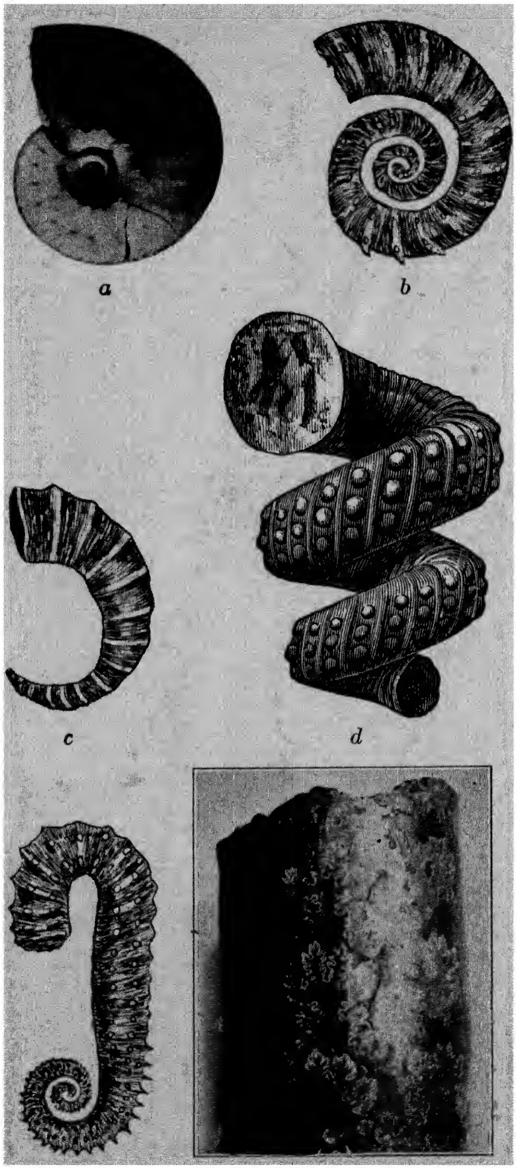


FIG. 195. Typical Cretaceous ammonites: *a*, *Placenticeras intercalare* (Meek); *b*, *Crioceras duvali*; *c*, *Toxaceras bituberculatum*; *d*, *Helioceras robertianus* (after Pictet); *e*, *Ancyloceras matheronianum*; *f*, *Baculites ovatus*, with outer shell removed to show sutures. (*d*, from Le Conte's "Geology," Courtesy of D. Appleton and Company.)

markable tendency to assume strange forms (Fig. 195). Some developed uncoiled shells; others spiral shapes; while still others were curved or actually straight (e.g. *Baculites*). Thus, externally at least, there was a reversion to the early Paleozoic forms, but in all cases they retained their complicated suture or partition structure. "These strange forms have been likened by Agassiz to death-contortions of the ammonite family; and such they really seem to be. . . . From the point of view of evolution, it is natural to suppose that under the gradually changing

Evolution of the Chamber-shelled (Tetrabranch) Cephalopods

QUATERNARY	Chamber-shelled cephalopods represented only by a few genera of close-coiled nautiloids, e.g. modern pearly Nautilus (Fig. 371).	
TERTIARY	Ammonoids very rare and in lowest Tertiary (Eocene) only.	Close coiled nautiloids only persist, e.g. Nautilus, but more varied than now.
CRETACEOUS	Ammonoids much like Jurassic though somewhat diminished and with straight forms, e.g. Baculites (Fig. 195), and curved or open-coiled forms more common.	
JURASSIC TRIASSIC	Ammonoids greatly advanced in numbers, species, and complexity of septa, and they reach their climax, e.g. Ceratites with scalloped septa (Fig. 193); ammonites with highly frilled septa (Fig. 194); and some curved and straight ammonoids.	Some nautiloids present, but Orthoceras becomes extinct in Triassic
PERMIAN	Ammonoids common, some showing distinctly increased (highly curved) complexity of septa, e.g. Waagenoceras (Fig. 127).	Nautiloids, including Orthoceras, persist, but subordinate.
MISSISSIPPIAN PENNSYLVANIAN	Much like Devonian, but complexity of septa in goniatites somewhat increased (Fig. 126).	Nautiloids still predominate.
DEVONIAN	Ammonoids first appear with only slight (angular) complexity of septa junctions, e.g. goniatite (Fig. 125).	Simpler forms (nautiloids) continue as in Silurian.
SILURIAN	Much like Ordovician. No ammonoids.	Coiled nautiloid forms predominate.
ORDOVICIAN	Close-coiled forms, e.g. Trocholites (Fig. 73d). Open-coiled forms, e.g. Trochoceras (Fig. 73c). Curved forms, e.g. Cyrtoceras (Fig. 73b). Straight forms, e.g. Orthoceras (Fig. 73a).	Straight forms predominate.
CAMBRIAN	Straight and curved forms only.	

conditions which evidently prevailed in Cretaceous times, this vigorous Mesozoic type would be compelled to assume a great variety of forms, in the vain attempt to adapt itself to the new environment, and thus to escape its inevitable destiny. The curve of its rise, culmination, and decline reached its highest point just before it was destroyed. The wave of its evolution crested and broke into strange forms at the moment of its dissolution."[1] Very few if any ammonites crossed the line into the early Cenozoic, and such an abrupt termination of so abundant and

FIG. 196. Internal shell of a belemnite, restored. (From Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

FIG. 197. A Jurassic belemnite, *Belemnoteuthis antiqua.* (Modified after Mantell.)

diversified a group of animals has rarely been equaled in the history of the animal kingdom.

Another important advance among the cephalopods was the appearance of the *dibranchs* in the Triassic. They are the highest of all mollusks, including modern "cuttlefishes." Jurassic dibranchs were exceedingly abundant both in numbers of species and of individuals. Most characteristic of these were the *Belemnites,* so called because of the long, conical, or dart-shaped, internal shells which are generally the only portions preserved in the fossil state (see Fig. 196). They were similar

[1] J. Le Conte: *Elements of Geology,* 5th ed., pp. 499-500.

in appearance to the modern squids or cuttlefishes. Some Jurassic forms reached a length of over two feet. A few specimens from the English Jurassic show almost perfect preservation of the original creature (see Fig. 197). Ink bags, like those found in modern squids, are sometimes so well preserved that drawings of the fossils have actually been made with ink taken from their own ink bags.

Belemnites declined greatly by the close of the Mesozoic.

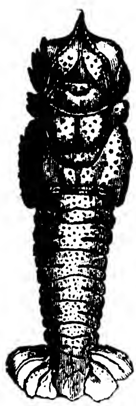


FIG. 198. A Triassic long-tailed decapod, *Pemphix Sueurii.* (From Naumann.)

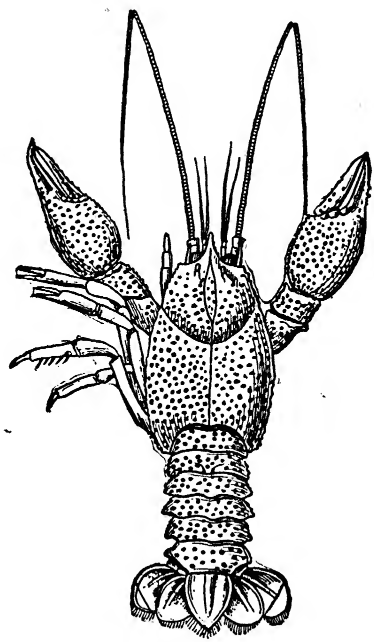


FIG. 199. A Jurassic long-tailed decapod (lobster). (After Neumayr's "Erdgeschichte," from Schuchert's "Historical Geology," courtesy of John Wiley and Sons.)

Arthropods. Of the *crustaceans* the trilobites, so important in the Paleozoic, did not continue into the Mesozoic. The *eucrustaceans,* however, showed a notable advance with the first appearance of the so-called long-tailed *decapods* (lobster family) in the Triassic. These rank among the highest of all crustaceans (Figs. 198, 199). During the Jurassic the lobster forms showed many genera and species, and the short-tailed decapods (crab family) made their first appearance. Many types intermediate between the long-tailed and short-tailed decapods were very

common, these connecting forms being of special evolutionary interest because, in the embryonic development of the modern crab, the long tail of the early stage gradually becomes shorter and practically absent in the adult stage. This is an excellent example of the so-called "Law of Recapitulation" (see Fig. 200). The short-tailed decapods increased notably during the Cretaceous.

Insects showed distinct progress in the Triassic by the addition of the *beetle* tribe which ranks high among the insects.

Hundreds of species of Jurassic insects are known. There were many of the simpler forms, such as *grasshoppers* and *cockroaches*. Among

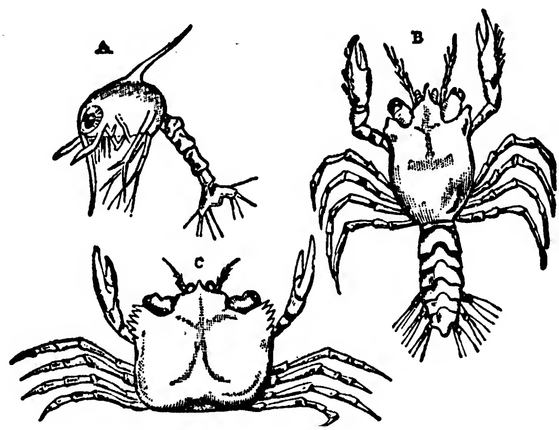


FIG. 200. Three stages in the life history of a modern crab. The larval stage *B* is very similar to the adult Jurassic form shown in Fig. 199. (After Couch, from Le Conte's "Geology," permission of D. Appleton and Company.)

higher forms the *beetles* became very abundant, while *flies* and still higher insects such as *bees, ants, butterflies,* and *moths* made their first appearance in the Jurassic. The insect life in the world was, therefore, remarkably modern in aspect thus far back in geological time.

FISHES AND AMPHIBIANS

Fishes. A very important advance took place among the fishes with the introduction of the true bony fishes, known as *teleosts,* during Jurassic time (Fig. 202). These comprise the most highly organized of all fishes, including such modern types as salmon, cod, and herring. They gradually evolved from the ganoids which latter continued to be the predominant fishes until Cretaceous time (Fig. 201). Since that

time the ganoids have dwindled almost to extinction, while the teleosts have become exceedingly profuse and diversified. The Jurassic teleosts were simple forms, not numerous, and frequently on the border between true ganoids and true teleosts. Cretaceous sharks, which were common and often large, have left an almost incredible number of fossil teeth.

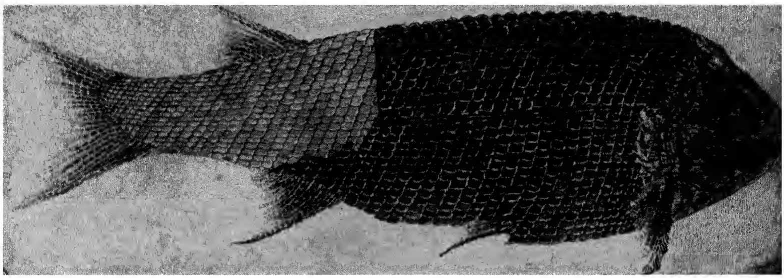


FIG. 201. A ganoid, *Catopterus redfieldi,* from the Triassic sandstone of Connecticut. (After Newberry, U. S. Geological Survey, Monograph 14.)

Amphibians. Though somewhat diminished as compared with the later Paleozoic, Triassic amphibians were numerous and often notable for their great size. In general they were much like the late Paleozoic forms. *Mastodonsaurus* attained a length of 15 or 20 feet and had a

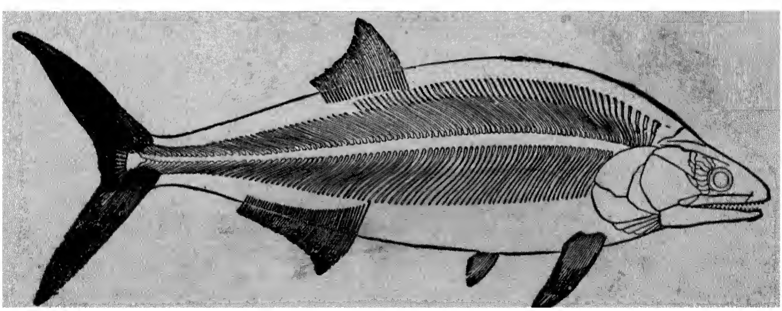


FIG. 202. A primitive or ancestral Jurassic teleost, *Hypsocormus insignis.* (From Scott's "Geology," courtesy of The Macmillan Company.)

skull 4 feet long. The Bunter series of Germany is particularly rich in fine fossil amphibians. By the close of the Triassic the amphibians had declined remarkably, so that among the land vertebrates, of which they were the ancestors, they never again assumed a position of importance. Comparatively few, relatively small forms, such as frogs, toads, and

salamanders, represent this once great class of animals at the present time.

Reptiles

General Statement. The Mesozoic era has been appropriately called the "Age of Reptiles," since those animals were at once the most characteristic and powerful creatures of the time. So far as known, the first true reptiles appeared in the Pennsylvanian. During the Mesozoic they rose to great prominence, both in number of individuals and diversity and size of forms; reached their culmination in the midst of the era;

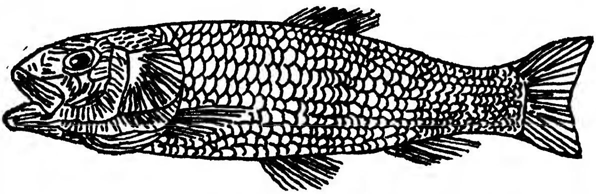


FIG. 203. A Cretaceous teleost fish, *Osmeroides lewesiensis,* restored.

and declined in a most remarkable manner toward the close of the era. During the Mesozoic the reptiles ruled all fields—sea, land, and air.

"The advance from the amphibian to the reptile was a long forward step in the evolution of the vertebrates. . . . Yet in advancing from the amphibian to the reptile the evolution of the vertebrate was far from finished. The cold-blooded, clumsy and sluggish, small-brained and unintelligent reptile is as far inferior to the higher mammals, whose day was still to come, as it is superior to the amphibian and the fish" (W. H. Norton).

Extinct Mesozoic Reptiles. The following grouping of certain characteristic, extinct Mesozoic reptiles is not meant to be an exact

1. ENALIOSAURS ("Sea-lizards") (Swimming reptiles)	e.g.	1. Ichthyosaur ("Fish-lizard"). 2. Plesiosaur ("Lizard-like"). 3. Mosasaur ("Meuse River lizard") (Later Mesozoic only).
2. DINOSAURS ("Terrible-lizards") (Walking reptiles)	e.g.	1. Sauropod ("Lizard-footed") (Not known from the Triassic). 2. Stegosaur ("Plated-lizard") (Not known from the Triassic). 3. Triceratops ("Three-horned face") (Later Mesozoic only). 4. Theropod ("Beast-footed") 5. Ornithopod ("Bird-footed") (Not known from the Triassic).
3. PTEROSAURS ("Winged-lizards") (Flying reptiles)	e.g.	1. Pteranodon ("Winged, toothless"). 2. Rhamphorhynchus ("Beaked-snout").

scientific classification. It is a simple arrangement for convenience of elementary discussion, and it is by no means complete. Unless otherwise stated, the types mentioned ranged through the whole Mesozoic era.

Enaliosaurs. There are many known types of these swimming reptiles, but only a few of the most typical and characteristic forms are chosen for description.

The *Ichthyosaurs* were fishlike forms which ranged in length up to 25 or 30 feet. They had stout bodies, very short necks, and large heads (Figs. 204, 205). The head, sometimes 4 or 5 feet long, had an elongated snout in which as many as 200 large sharp teeth were set in

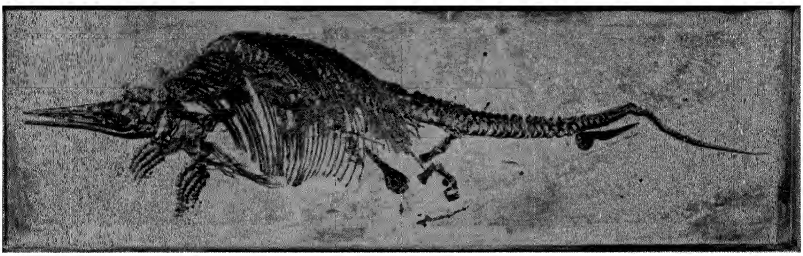


FIG. 204. A remarkably preserved skeleton of a Jurassic ichthyosaur. It contains parts of several skeletons of unborn young. It is about 12 feet long. (Courtesy of the American Museum of Natural History.)

grooves. In some forms comparatively small eyes, and in others enormous ones, sometimes over a foot in diameter, were protected by bony plates. A powerful tail with two lobes set vertically had the vertebral column extending through the lower lobe. The four limbs were perfectly converted into swimming paddles, thus strongly suggesting that these, as well as other enaliosaurs, represented former land reptiles which adapted themselves to a water environment much like certain mammals of today, such as whales and dolphins. Fishes and cephalopods were largely their prey, as proved by the fossil contents of their stomachs, no less than 200 belemnite remains having been found in one specimen alone. Many remarkably preserved specimens of ichthyosaurs have been discovered (Fig. 204), some with even the embryos plainly visible within the bodies. Ichthyosaurs ranged through the whole Mesozoic.

Plesiosaurs were less powerful forms than ichthyosaurs, though they were usually longer, some having attained a maximum length of 40 to 50 feet (Fig. 206). A stout body, long, slender neck, small head, short tail, and four powerful paddles were characteristic features. Sharp

teeth were set in sockets (not grooves) in the jaw. With their slender, serpent-like necks, often 10 to 20 feet long, "the Plesiosaurs could lie motionless far below the surface, occasionally raising their heads above the water to breathe, or darting them to the bottom after their prey,

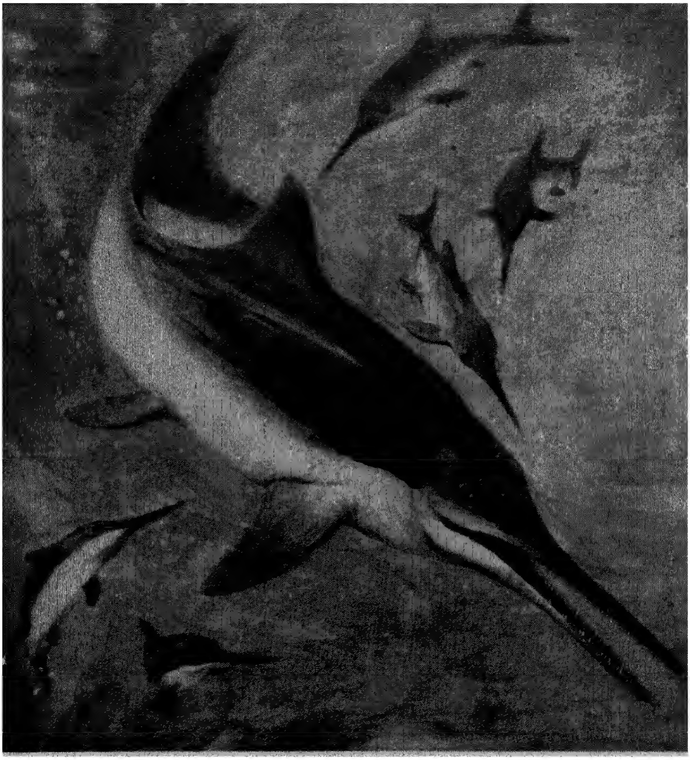


FIG. 205. A group of ichthyosaurs, *Ichthyosaurus quadricissus,* of the enaliosaur division of Mesozoic reptiles. Maximum length 25 to 30 feet. Restoration by C. R. Knight, under the direction of H. F. Osborn. (By permission of the American Museum of Natural History.)

which consisted chiefly of flesh" (W. B. Scott). Plesiosaurs ranged through the whole Mesozoic.

Mosasaurs were true "sea-serpents" or carnivorous marine reptiles which often reached a length of from 40 to 75 feet (Fig. 207). Though now wholly extinct, they were closely related to snakes and lizards in structure. The four limbs were converted into short, stout, swimming paddles, and their jaws were set with sharp teeth. The relatively smaller

head, long, slender body, and different tail structure distinguished the mosasaurs from the ichthyosaurs, as a comparison of the accompanying pictures will show. Mosasaurs existed during the latter portion only of the Mesozoic.

Dinosaurs. These Mesozoic reptiles comprised a great variety of forms as regards both shape and size. Only five of the more common and characteristic types have been selected for description. Like most other reptiles, the dinosaurs laid eggs, fossilized specimens of which have been found.

The *sauropods* were the largest of all Mesozoic reptiles, and in fact they included the largest animals which ever trod the earth. Well-

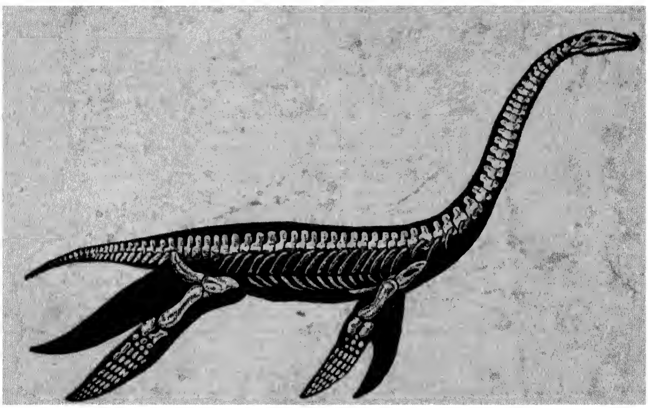


FIG. 206. A restored plesiosaur, *Plesiosaurus dolichodeirus,* of the enaliosaur division of Mesozoic reptiles. Maximum length 40 to 50 feet. (From Le Conte's "Geology," courtesy of D. Appleton and Company.)

preserved specimens are known whose lengths are from 75 to 90 feet, and recently one has been discovered in Utah which it is thought will, when mounted, show a length of over 100 feet. It has been estimated that one of the largest brutes must have weighed about 40 tons. They had extremely long necks and tails, very small heads and brains, and four great legs. Thigh bones 7 feet long are known. They were five-toed and plantigrade, and doubtless walked with their bodies well above the ground. Some were exceptionally long and slender (Fig. 208), but certain others, shorter and more massive, were heavier. All were plant-eaters provided with grinding teeth. Sauropods ranged through Jurassic and Cretaceous times.

The *stegosaurs* are so named because of the double row of great bony plates on the back of each of these most remarkable brutes (Fig. 210)

FIG. 207. A mosasaur, *Tylosaurus dyspelor,* of the enaliosaur division of Mesozoic reptiles. Maximum length about 75 feet. Restoration by C. R. Knight under the direction of H. F. Osborn. (Courtesy of the American Museum of Natural History, from Scott's "Geology," by permission of The Macmillan Company.)

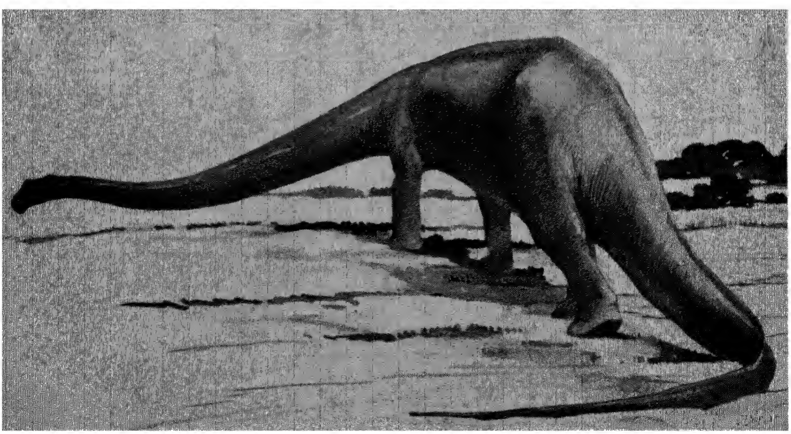


FIG. 208. The longest of all known dinosaurs, a sauropod, *Diplodocus.* A mounted skeleton in the Carnegie Museum of Pittsburgh measures 87 feet long. Restored by C. R. Knight under the direction of H. F. Osborn. (Courtesy of the American Museum of Natural History.)

FIG. 209. Unearthing dinosaur bones in Bone Cabin Quarry, Wyoming. (Courtesy of the American Museum of Natural History.)

FIG. 210. A stegosaur, an armed dinosaur. Maximum length, 30 to 40 feet. Restored by C. R. Knight. (Courtesy of the American Museum of Natural History.)

which attained a maximum length of 30 to 40 feet. The long, powerful tail had pairs of long spines toward the end instead of plates. As compared with the sauropods the neck was short. They were quadrupedal, four-toed in front, and three-toed in the rear. All were plant-eaters. The brains of all dinosaurs were almost incredibly small, even as compared with modern reptiles, and this was particularly true of stegosaurs. The stegosaurs ranged through Jurassic and Early Cretaceous times.

Triceratops was another strange-looking creature, so named because of its three horns—two of great size just back of the eyes and a smaller

Fig. 211. Restoration of a great two-legged theropod dinosaur (***Tyrannosaurus***) and several four-legged dinosaurs (*Triceratops*) from the Cretaceous strata of Montana. Tyrannosaurus, nearly 50 feet long, was the greatest carnivorous land animal of all known time. Painted by C. R. Knight under the direction of H. F. Osborn. (Courtesy of the American Museum of Natural History.)

one on the nose (see Fig. 211). The enormous flattened skull had a sharp beak in front. The skull extended backward into an immense hood or capelike structure. According to Marsh they (Triceratops) had the largest heads and smallest brains of the reptiles, and hence they must have been exceedingly stupid. Skulls 6 or 8 feet long have been found. The four legs and the tail were massive and powerful. This creature attained a length of fully 25 feet, and it had a bulk about twice that of an elephant. It was a plant-eater and probably not as ferocious as it looked. Good specimens have been found in the western interior of

the United States. Triceratops existed only during the Cretaceous period.

Theropods were carnivorous dinosaurs, as proved by their numerous sharp teeth set in comparatively large heads (see Fig. 211). They were bipedal, that is, they walked on two legs, the front limbs having been very small and used only for grasping. The toes were armed with sharp claws. The bipedal habit combined with the long, ponderous tail gave them a sort of kangaroo aspect. The limb bones were hollow, thus suggesting a birdlike structure. In fact before it was known that the numerous tracks in the Newark sandstone of the Connecticut Valley were made by creatures of this sort, they were called bird-tracks. Theopods varied in length from 3 to nearly 50 feet, and though much smaller than many other dinosaurs, they were probably the most ferocious of all, and they more than likely preyed upon the much larger plant-eaters. A mounted skeleton of one of these creatures, called *Tyrannosaurus,* in the American Museum of Natural History is 47 feet long. It represents the greatest known flesh-eating land animal of all time. The theropods lived through the whole Mesozoic, and they have been found in many parts of the world.

Ornithopods were in general appearance much like the theropods, but they were plant-eaters, as shown by the tooth structure. They were bipedal, the hind limbs having only three functional toes, giving a sort of birdlike track. The largest of these creatures measured 30 feet in length, and when walking they must have stood 15 or 20 feet high. Ornithopods ranged through all of the Mesozoic except the Triassic.

Dinosaur Footprints. Dinosaurs often left footprints on exposed mud-flats during Mesozoic time. In some cases the tracked surfaces, after drying in the sun, were covered by deposits left by succeeding flood waters. Such tracks are found here and there through thousands of feet of Triassic strata in the Connecticut Valley. Such footprint-bearing strata are fine illustrations of the remarkable detail in which some geological records may be preserved. An excellent outcrop, about 30 by 150 feet in size, may be seen close to the road a few miles north of Holyoke, Massachusetts. Dozens of tracks, made by several sizes and species of two-legged dinosaurs, may be seen in an amazing state of perfection on the surface of this ledge. The tracks, which are three-toed, range in length from 3 to 16 inches (Fig. 212). Ripple marks, and even raindrop impressions, also occur.

Dinosaur tracks of Triassic age are well shown near Tuba City, Arizona.

Scores of tracks, made by several species of dinosaurs, have been found on outcrops of Cretaceous sandstone in Peace River Canyon, British Columbia.

Most remarkable for size are those occurring in coal-bearing strata of Cretaceous age at Standardville, Utah. The largest of these tracks, over

FIG. 212. Tracks of a large two-legged dinosaur on Triassic sandstone from the Connecticut Valley, showing how both feet slid some distance in the soft material after which the creature suddenly sat down, the end of the backbone having left a distinct impression. (After Edward Hitchcock.)

4 feet long, were made by a great two-legged creature with a stride of 12 feet! (Fig. 213). The bones of this creature have not been found. It was probably a plant-eater.

Dinosaur Eggs. It is definitely known that some of the dinosaurs laid eggs. "The fossil eggs were found in Madagascar (many) years

ago, . . . and more recently they have been found in old (Cretaceous) sands which were dune sands in Mongolia millions of years ago, so that the presumption is strong that they all laid eggs" (E. W. Berry). Still later some fragments of shells were found in Wyoming.

The finest collections were obtained in Mongolia by the American Museum of Natural History expeditions. These eggs, elongate and

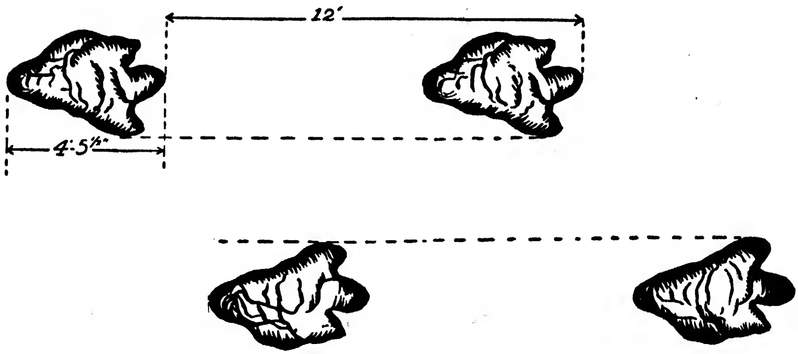


FIG. 213. A sketch of footprints, each over 4 feet long, left by a great two-legged dinosaur with a stride of 12 feet. Found in coal-bearing Cretaceous strata at Standardville, Utah. (After C. N. Strevell.)

nearly a foot long (Fig. 214), were laid by comparatively small, four-legged, horned dinosaurs (Protoceratops), skeletons of which were also found.

Dinosaur Brains. Dinosaurs in general must have been exceedingly stupid creatures because their brains, relative to size of the animal, were amazingly small. A big modern elephant has a brain weighing about 8 pounds, but a still bigger stegosaur had a brain weighing less than 3 ounces! A great sauropod (Fig. 208), nearly 90 feet long and fully 25 tons in weight, had a brain about as large as a hen's egg. As if to partially make up for such a tiny brain, there was a much bigger mass of spinal material (sacral ganglion) concentrated over the hind legs. This was probably necessary in order to control the rear part of the huge bulk, especially the great hind legs and tail. This was not, however, true brain material.

Extinction of the Dinosaurs. One of the most astonishing events in the history of animal life was the extinction of the mighty dinosaurs. After ruling the lands for scores of millions of years, through a whole geologic era, they completely vanished from the earth in a remarkably short time.

Several factors probably contributed to their extinction. Probably their great size was a factor for it is well known "that while very large animals spend nearly all their time in eating, small animals spend a small proportion of theirs, and most of it in other activities. Now, as long as food is abundant, the larger animals of a race have the better chances, but if a scarcity of food ensues, the larger animals may all be suddenly swept out of existence." (W. D. Matthew).

Fig. 214. Dinosaur eggs weathering out of a cliff of Cretaceous strata in Mongolia. (Courtesy of the American Museum of Natural History.)

An important factor no doubt was the great uplift of lands at the time of the Rocky Mountain Revolution in North America, and in many other parts of the world, causing profound topographic and climatic changes in the habitats of the dinosaurs. Thus the browsing grounds of these reptiles were often literally wiped out as such—broad lowlands giving way to mountains; mild, moist climate changing to cold or dry; and rich vegetation for food supply being much reduced. The dinosaurs had to adapt themselves to the changing conditions or disappear from the earth. They faced the test and failed completely.

Another factor probably was the rise of the small but more agile, more intelligent mammals which very likely ate the dinosaur eggs left in unguarded nests.

Without doubt their low intelligence, as shown by their amazingly small brains, also proved to be a serious handicap.

Pterosaurs. These were real "flying-dragons" in Mesozoic time. They varied greatly in size from about that of a sparrow to others with

a spread of wing of 25 feet, which is about twice that of any modern bird. Not only did they include the largest creatures which ever flew but, on account of their hollow bones, their skeletons were wonderfully light. One finger of each front limb was enormously lengthened to support the flying membrane, as shown in Fig. 215. The other fingers were

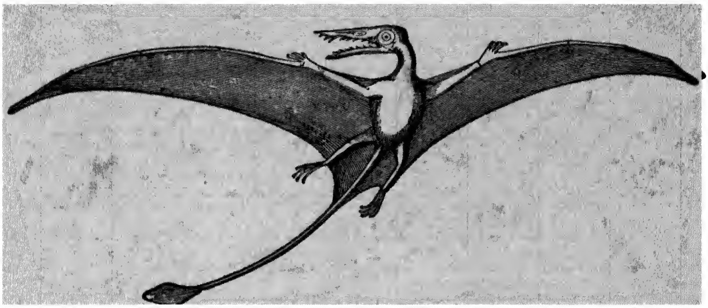


FIG. 215. Restoration of a *Rhamphorhynchus* of the pterosaur division of Mesozoic reptiles. Spread of wing about 2 feet. (Restored by Marsh.)

armed with sharp claws. In general we may recognize two groups. One group, typified by the *Pteranodon* (Fig. 216), had a short, stout body, short tail, and moderately long neck. The earlier Mesozoic forms were supplied with sharp teeth, while the Cretaceous forms were mostly

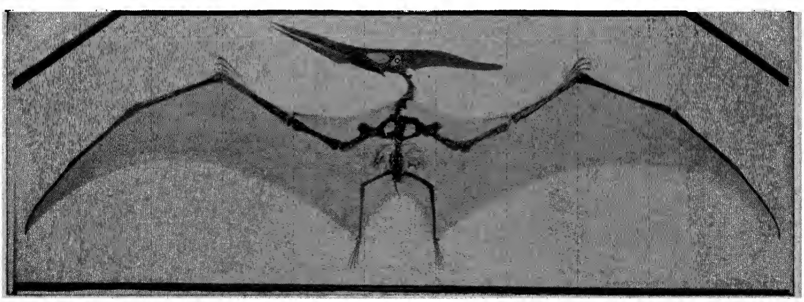


FIG. 216. Skeleton of a Cretaceous pterosaur known as *Pteranodon*. This great flying reptile, with a wing-spread of nearly 25 feet, was the largest of all known flying creatures. Note the impressions of the membranous wings. (Courtesy of the American Museum of Natural History.)

toothless. The other group, typified by the *Rhamphorhynchus* (Fig. 215), had long tails, and in one species at least the end of the tail was expanded into a sort of rudder. Many wonderfully preserved specimens of pterosaurs have been found, some with even the wing membranes

preserved. Pterosaurs ranged from the Late Triassic to the close of the Mesozoic.

Surviving Mesozoic Reptile Groups. Though overwhelmed by the reptiles above described and of less peculiar interest because they represent groups still living, certain other Mesozoic reptiles deserve brief mention.

Turtles date back at least to the Middle Triassic, and even those very early forms clearly showed the familiar structure which easily separates them from other reptiles.

Lizards are known even from the Triassic, and, though they ranged through the Mesozoic, they were always small and comparatively rare.

Crocodiles made their first appearance in the Jurassic, and some were marine forms. In appearance they resembled the modern gavial of India, particularly as regards the long, slender snout. Crocodiles were numerous from the Jurassic to the end of the Mesozoic.

Snakes are not known to have appeared till late in the Cretaceous, and those early forms were small and comparatively rare.

Birds

A very important feature from the standpoint of evolution was the introduction of the feathered creatures in the Jurassic. "The class of birds is now so distinctly separated from all others and the connecting links obliterated, that the earliest birds are of especial interest as throwing light on the evolution of this class. Until 1862 birds had been found only in the Tertiary, and these were already distinctly differentiated as typical birds. But in that year there was found in the Solenhofen (Bavaria) limestone, so celebrated for its marvelous preservations of organisms, a flying feathered biped, and therefore presumably a bird. But how different from our usual conceptions of this class! Along with its distinctive bird-characters of feet, limb-bones, beak, and especially of feathered wings, it had the long tail and toothed jaws (see Fig. 217) of a reptile. The structure of the tail is especially significant. In ordinary birds the tail proper is shortened up to a rudiment and ends in a large bone, from which radiate the feathers of the tail-fan. In this earliest bird, on the contrary, the tail proper is as long as all the rest of the vertebral column put together, consisting, as seen in the figure, of twenty-one joints from which the fan feathers come off in pairs on each side. The tail-fan of this bird differs from that of typical birds precisely as the tail-fin of the earliest fishes differs from that of typical

fishes. The tail-fan of this earliest bird, like the tail-fin of the earliest fishes, was vertebrated. This wonderful reptilian bird was called Archeopteryx ('primordial winged creature'), and the species macrura ('long-tailed'). . . . So complete is the mixture of the two kinds of characters that some zoölogists believe that the reptilian characters predominate, and that it should be called a birdlike reptile. Most agree, however, that it is a reptilian bird."[1] Thus, while the evidence seems conclusive that birds were evolved from reptiles, there is no conclusive evidence that they were derived from the flying reptiles (pterosaurs).

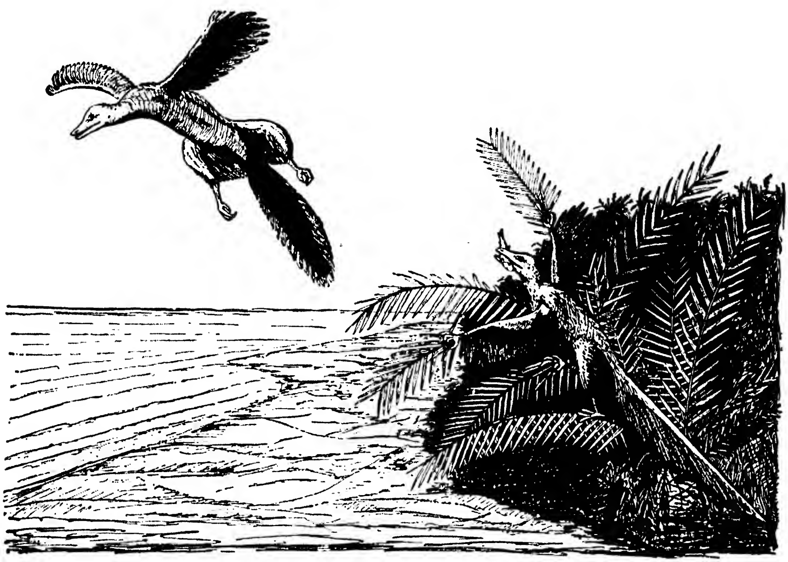


FIG. 217. Restoration of the earliest known bird (*Archeopteryx*) from the Jurassic. (After E. W. Berry, from his textbook of "Paleontology.")

Rather there appears to have been a development of these two remarkable groups of flying creatures alongside each other.

During the long time between the Jurassic, when the first known birds appeared, and the Late Cretaceous, important evolutionary changes took place in this class of animals, though fossils of the interval are almost, if not wholly, absent. Cretaceous birds were distinctly more advanced and modern in appearance than were those of the Jurassic. Thus the long, vertebrated tail of the earlier forms had become greatly shortened, and the only important primitive characteristic which they retained

[1] J. Le Conte: *Elements of Geology,* 5th ed., pp. 462-463.

was the possession of teeth. Compared with modern birds, they had much smaller brain cavities.

At least 30 species of Cretaceous birds are known, all of these belonging to two great, though very different, groups (orders) e.g. *Ichthyornis* and *Hesperornis.* All appear to have been aquatic forms. The *Ichthyornis* types were powerful fliers as proved by the strongly developed keel and wing bones. The teeth were set in distinct sockets. The structure (biconcave) of their vertebræ was quite distinctly reptilian. They averaged about the size of a pigeon (see Fig. 218).

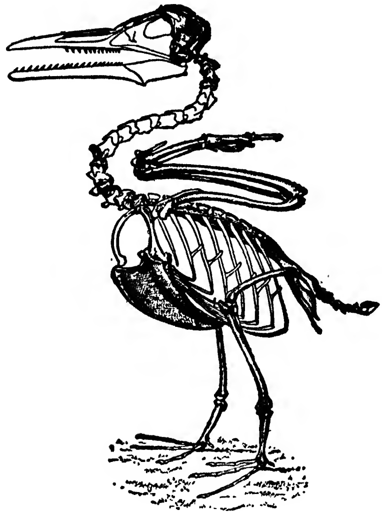


FIG. 218. A Cretaceous toothed bird, *Ichthyornis victor.* Height, about 9 inches. (After Marsh.)

Hesperornis comprised forms incapable of flight, but often of great size—five to six feet in length. In marked contrast with the Ichthyornis, these forms had powerfully developed legs which served as swimming paddles in these almost wholly aquatic forms. In every way they were adapted to rapid swimming. Their teeth were set in grooves instead of sockets.

MAMMALS

A very important event in the history of animal life was the first appearance of *mammals* in the Early Mesozoic. Mammals comprise the highest class of all animals. They are characterized by suckling their young and having hair on their bodies. For convenience of discussion we shall consider them in three categories as follows: (1) *monotremes* or egg-laying forms, such as the modern spiny ant-eater; (2) *marsupials* (e.g. opossum and kangaroo) or those giving birth to imperfectly formed young which are carried for some time in a pouch (marsupium) by the mother; and (3) *placentals* (e.g. dog, horse, and man) or those giving birth to well-formed young which, in a prenatal condition, are attached to the mother by the placentum.

Throughout the Mesozoic era the mammals occupied a very subor-

dinate position among animals. They seem to have been almost completely overshadowed by the hordes of reptiles.

The earliest (Triassic) representatives were small, very primitive forms of reptilian mammals, belonging to the low-order monotremes. They, like the birds, evolved from certain types of reptiles, various transitional forms between reptiles and mammals being known from the fossil record. The primitive Triassic mammals were not numerous, and only a few genera are known to have existed.

Triassic mammals scarcely suggested their later (Cenozoic) development into the manifold, and most powerful and intelligent, creatures of the earth. "It is one of the most striking generalizations of paleontology that the upwelling of future organic rulers begins in unobtrusive small forms. In all stocks of plants and animals such potential rulers are always present" (C. Schuchert). This was distinctly true of the fishes, amphibians, reptiles, and mammals.

Jurassic mammals continued to be represented by comparatively few, small, primitive forms, but, in addition to the monotremes, there were some archaic or ancestral marsupials. According to the scant records, Jurassic mammals were no larger than mice or rats, and all were low in body organization.

Cretaceous time witnessed important advances among the mammals. Monotremes were much as in the earlier Mesozoic, but typical marsupials, belonging to the opossum family, were introduced. Most important, however, was the appearance of the oldest known placental mammals in the Late Cretaceous. These were represented by some very low-order, primitive forms called *insectivores* (ant-eaters). Certain surviving relatives of these live in Madagascar. "Somewhere in Late Cretaceous time a group of small placental insectivores (tree shrews) took to climbing up trees, with momentous consequences, for here they gradually acquired those primary arboreal characters which, as there is much evidence to conclude, were deeply stamped into the anatomy and ways of life of our own remote ancestors" (W. K. Gregory).

Just before the close of the Cretaceous period, certain other forms of slightly less primitive, low-order, placental mammals appeared.

CHAPTER XXIII

SUMMARY OF MESOZOIC HISTORY AND LIFE

ALTHOUGH the Mesozoic was quite certainly shorter than the Paleozoic, it had, nevertheless, an estimated duration of about 150,000,000 years. As the name indicates, the Mesozoic was the era of transition between the Paleozoic and the Cenozoic. Eastern North America had been to a large degree completed at the time of the Appalachian Revolution, except for the addition of the Atlantic and Gulf Coastal Plain belts. In western North America, however, profound physical geography changes took place, bringing that part of the continent almost to its present condition, as regards relations of land and sea, only near the close of the Mesozoic. The life of the Mesozoic, too, was distinctly intermediate in character, those of the great groups of characteristic Paleozoic organisms which did continue into the Mesozoic having become extinct during the era, while many more modern groups showed great development during the era. Certain other important groups of organisms like the cycads, ammonites, and reptiles, were eminently characteristic of the Mesozoic and reached their culmination during the era.

MESOZOIC ROCKS

The late Triassic stratified rocks of the Atlantic Coast are sandstones, conglomerates, and shales, mostly of continental origin, though in part at least probably of estuarine origin. Rocks of the Triassic in the western interior are chiefly the "Red Beds" (shales, sandstones, and limestones), with more or less salt and gypsum, of terrestrial or lacustrine origin. On the Pacific Coast, Triassic marine strata are prominently developed from southern Alaska to Lower California.

No Jurassic rocks occur in the eastern one-half of the continent. Widespread Jurassic strata in the western interior are very largely of continental origin, part of the Upper Jurassic being of marine origin. Jurassic marine strata are prominently developed on the Pacific Coast.

Lower Cretaceous strata occur in the Atlantic Coastal Plain region, where they consist almost entirely of unconsolidated sands and

clays of continental origin. The Lower Cretaceous strata in the Texan region are made up chiefly of more or less consolidated sands, sandstones, and chalky limestones of marine origin, with continental deposits at the base. In the western interior regions of both the United States and Canada, the strata rather doubtfully of this age are probably of continental origin. On the Pacific Coast there are great thicknesses of marine Lower Cretaceous strata.

Upper Cretaceous deposits of the Atlantic and eastern Gulf regions are mostly sands, clays, marls, and greensands, with some chalky limestones toward the south. These are very largely of marine origin. In Texas and the western interior the Upper Cretaceous beds are there mostly marine sandstones, shales, and chalky limestones, though some continental deposits (including coal) also occur, especially in the latest Cretaceous. On the Pacific Coast typical marine beds are grandly displayed.

Some igneous rocks, both volcanic and intrusive, occur in the Atlantic Coast Triassic. Large quantities of volcanic rocks of Triassic and Jurassic ages, and some of Cretaceous age, occur on the Pacific Coast, especially in British Columbia. Tremendous masses of Late Jurassic granite and diorite occur on the Pacific Coast in the form of many large and small batholiths.

In general the thickness of the Mesozoic group of rocks is not nearly as great as that of the Paleozoic, but more locally remarkable thicknesses of strata are represented in even single systems, as in the case of the Triassic beds of the Atlantic border (10,000 to 15,000 feet thick), or the Cretaceous beds of the Pacific border (fully 20,000 to 40,000 feet).

Physical History

Relations of Land and Sea. Throughout the era, except during parts of the Cretaceous, North America was very largely dry land, thus being in marked contrast with the Paleozoic condition of the continent. The eastern half or two-thirds of the continent, except the Atlantic and Gulf borders during part of the Cretaceous, was continually dry land, while the western part of the continent was subject to varying marine, estuarine, lacustrine, and desert-basin conditions. The reader should review the paleogeographic maps.

Early in the Mesozoic era, or Triassic period, eastern North America was all dry land; continental and some marine deposits were forming in the western interior of the United States; and the Pacific border was

mostly occupied by marine waters. Later in the Triassic the same conditions prevailed in the west, but long, narrow troughs were formed along the Atlantic side in which were deposited the thick continental and estuarine (Newark) deposits. At the close of the Triassic, or beginning of the Jurassic, there was enough crustal movement to convert the basins (Newark) of deposition in the east into dry land, while on the Pacific Coast the sea withdrew, thus leaving the whole continent land.

During the Jurassic the Pacific Coast again showed a strong tendency to be submerged, and in the Late Jurassic a transgression of the sea took place from Alaska southward over the Rocky Mountain region as far as central Arizona. During the whole Jurassic eastern North America was land, and at the close of the period the whole continent was land.

During the Early Cretaceous there was enough subsidence of the Atlantic and eastern Gulf borders to produce flood-plains, lakes, and marshes in which were deposited the Potomac series of sands, gravels, clays, etc. About the same time the continental (Trinity) deposits, followed by the marine Fredericksburg and Washita beds, were accumulating over the western Gulf (Texan) regions and southern western interior regions, and continental deposits were forming over the northern western interior region just west of the site of the Rockies. During the Early Cretaceous on the Pacific border there accumulated very thick marine deposits just west of the newly formed Sierra Nevada, especially in the Great Valley of California. Marine deposition also took place along much of the coast north of California.

The Early Cretaceous closed, or the Late Cretaceous opened, with the eastern part of the continent all undergoing erosion; a general submergence of the western Gulf (Texan) and southern western interior regions; and considerable deformation and uplift of the strata in parts of the Coast Range district.

Early in the Late Cretaceous, marine waters spread over practically all of the Atlantic and eastern Gulf Coastal Plain areas. At the same time "Appalachia," which had been so long persistent, became submerged under the Atlantic Ocean. The western Gulf and western interior districts were marked by a vast transgression of the sea from the Gulf to the Arctic, while the Pacific border continued as in the late Early Cretaceous.

During still later Cretaceous time there was a general withdrawal of the seas from North America, leaving all land at the end of the period.

Mountain Making. The Jurassic period was closed in the west by the "Sierra Nevada Revolution," when strata of great thickness were folded into mountains along the present sites of the Sierra Nevada and Cascade Mountains. There was also much deformation in many other parts of the Pacific Coast.

The Mesozoic era was closed by one of the most profound physical disturbances in the post-Proterozoic history of North America, if not in the world,—the "Rocky Mountain Revolution,"—when strata were more or less deformed by folding and faulting throughout much of the Rocky Mountain system. At the same time the whole eastern side of the United States, including the Appalachians, which had been worn down to a lowland by Middle Cretaceous time, and partly covered with Late Cretaceous sediments, was notably upwarped.

Igneous Activity.—While the later Triassic (Newark) sandstones were forming on the Atlantic Coast, there were considerable intrusions and extrusions of igneous rocks, now represented by such masses as the Palisades of the Hudson and the Holyoke Range of Massachusetts.

Great masses of plutonic igneous rock were intruded during Late Jurassic time as an accompaniment of the Sierra Nevada Revolution, and there was much volcanic activity in the western part of the continent during Mesozoic time.

Accompanying the Rocky Mountain Revolution there was much igneous activity in the western portion of the continent.

Climate

The character and distribution of organic remains, both plant and animal, rather clearly prove the climate of the Mesozoic to have been generally mild to possibly even warm temperate, with an appreciable distinction of climatic zones, though not at all comparable to those of the present. Temperate-climate plants of the Late Cretaceous are found even within the Arctic circle.

In earlier Mesozoic time arid climate conditions must have prevailed over the western interior of the United States, as shown by the "Red Beds" with some salt and gypsum.

In both the Early Jurassic and the Early Cretaceous, temperatures were sometimes below normal in parts of the world.

Early Cretaceous glaciers existed in Australia.

Life History

"The life of the Mesozoic constitutes a very distinctly marked assemblage of types, differing both from their predecessors of the Paleozoic and their successors of the Cenozoic. In the course of the era the plants and marine invertebrates attained substantially their modern condition, though the vertebrates remained throughout the era very different from later ones. Even in the vertebrates, however, the beginning of the newer order of things may be traced" (W. B. Scott).

Among plants the ferns, cycads, and conifers predominated during the earlier Mesozoic, but later in the era the angiosperms, including both monocotyledons and dicotyledons, first appeared and very soon predominated.

Among animals the absence of certain characteristic Paleozoic groups should be noted, such as cystoids, blastoids, trilobites, and eurypterids. Other Paleozoic groups continued into the early Mesozoic and then either became extinct or very greatly diminished such as the ancient corals (Tetracoralla), brachiopods, orthoceras, and amphibians. Some of the more important groups which made their first appearance in the Mesozoic era and developed notably were modern echinoids (e.g. sea urchins), modern eucrustaceans (e.g. lobsters and crabs), highest insects, teleost fishes, primitive birds, and small, primitive mammals. Reptiles, which began in the very late Paleozoic, developed marvellously during the era, thus justifying the application of the term "Age of Reptiles" to the Mesozoic.

As was the case toward the close of the Paleozoic era, so the mighty crustal disturbances of mountain-making and general uplift which affected many portions of the earth in Late Mesozoic and Early Cenozoic time produced profound changes in the natural environment, which in turn caused important changes in the organic world. The rule of the mighty enaliosaurs, dinosaurs, and pterosaurs gave way to the reign of the more intelligent mammals; angiosperms dominated the plant world; belemnites, the marvelous group of ammonoids, and the true toothed birds disappeared; the highest types of insects appeared; and teleosts prevailed among the fishes.

On the accompanying chart the author has brought together in concise form the salient facts regarding the life of the Mesozoic. In regular order, the principal successive changes in the sub-kingdoms and classes of plants and animals are graphically represented.

TABULAR SUMMARY OF MESOZOIC LIFE

	Plants	*Protozoans*	*Porifers and Cœlenterates*	*Echinoderms*	*Molluscoids*	*Mollusks*	*Arthropods*	*Vertebrates*
Cretaceous	Seedless plants and gymnosperms: Much like earlier Mesozoic. Angiosperms: Monocotyledons and dicotyledons attain supremacy among plants.	Foraminifers and radiolarians: Profuse.	Sponges and corals: Abundant and much like those of the Jurassic.	Crinoids: Greatly reduced. Asterozoans: Present. Echinoids: Both regular and irregular forms common.	Bryozoans: Present. Brachiopods: Only a few genera and species remain, and these are of rather modern aspect.	Pelecypods and gastropods: Abundant and similar to Jurassic, but more modern. Cephalopods: Still very abundant and much like those of the Jurassic with uncoiled to even straight ammonoids (e.g., Baculites) common. Ammonoids and belemnites become extinct. Dibranchs common.	Eucrustaceans: Much like Jurassic, but brachyurans (crabs) greatly increased. Insects: Much like Jurassic but even more modern types appear.	Fishes: Selachians abundant; dipnoans rare; ganoids common; teleosts predominate. Amphibians: Very subordinate. Reptiles: Abundant, but enaliosaurs, dinosaurs, and pterosaurs become extinct. Snakes appear. Birds: Much increased. Mammals: Simple, rare: primitive placentals.
Jurassic	Seedless plants: Much like Triassic. Gymnosperms: Cycads culminate; conifers more modern in aspect. Primitive angiosperms?	Foraminifers and radiolarians: Very abundant and highly diversified.	Sponges: Very abundant. Corals: Abundant and all are Hexacoralla of modern appearance.	Crinoids: Very profuse and notably large. Asterozoans: Present and of modern appearance. Echinoids: Abundant, with first irregular, more modern forms.	Bryozoans: Present. Brachiopods: Still more diminished and not many species.	Pelecypods: Similar to Triassic, but increased Gastropods: Ditto. Cephalopods: Nautiloids of coiled forms only and common; ammonoids (e.g., ammonites) culminate, with development of some uncoiled to even straight forms; dibranchs become profuse (e.g., belemnites).	Eucrustaceans: Macrurans (e.g., lobsters) common, and brachyurans (e.g., crabs) first appear, though rare. Insects: Abundant and diversified; first appearance of highest forms, e.g., flies, butterflies, ants, bees, and moths.	Fishes: Selachians common; dipnoans rare; ganoids common; teleosts first appear, but rare. Amphibians: Fossils? Reptiles: Much like Triassic, but more common and varied. Birds: First appear (e.g., Archeopteryx). Mammals: Simple, rare.
Triassic	Thallophytes. Bryophytes. Pteridophytes and arthrophytes: Common. Lepidophytes: Rare. Gymnosperms: Pteridosperms and cordaites become extinct; cycads and conifers prominent.	Foraminifers and radiolarians: Present.	Sponges: Present Corals: Very abundant, especially the more modern Hexacoralla; ancient Tetracoralla become extinct.	Crinoids: Common. Asterozoans: Present. Echinoids: Common and all are regular forms of ancient aspect.	Bryozoans: Present. Brachiopods: Greatly diminished and those with curved-hinge lines prevail for the first time.	Pelecypods and gastropods: Prominent and assume more distinctly modern aspect. Cephalopods: Nautiloids common with straight forms (orthoceras) becoming extinct; ammonoids common, with complex sutures (e.g., ceratites and ammonites); dibranchs first appear.	Eucrustaceans: Macrurans (e.g., lobsters) first appear. Insects: Common and mostly simpler forms but first beetles appear.	Fishes: Selachians, dipnoans and ganoids much as in late Paleozoic time. Amphibians: Declining, but large. Reptiles: Abundant and varied, e.g., enaliosaurs, dinosaurs, and pterosaurs; first turtles and lizards. Mammals: First and rare.

CENOZOIC ERA

CHAPTER XXIV

ROCKS AND PHYSICAL HISTORY OF THE CENOZOIC (EXCLUDING PLEISTOCENE GLACIATION)

General Statement

The Cenozoic era not only is the last one of geologic time, but also it is the shortest, with an estimated duration of 50 to 60 million years. During this short era the relief features of the earth have been revolutionized and brought to their present-day condition. It is doubtful if a single landscape feature of today was in existence as such prior to the opening of the era. Thus the face of North America has been completely made over in Cenozoic time. All mountains, hills, valleys, canyons, plateaus, and plains have assumed their present-day sizes and shapes; all existing lakes, shorelines, and waterfalls have been formed; the modern climatic zones have developed; and plants and animals (particularly mammals) have evolved to their modern condition.

Origin of Name and Subdivisions

Following are the subdivisions of the Cenozoic era now commonly recognized throughout the world:

CENOZOIC ERA	Quaternary period	2. Recent (post-Glacial) epoch
		1. Pleistocene (Glacial) epoch
	Tertiary period	4. Pliocene epoch
		3. Miocene epoch
		2. Oligocene epoch
		1. Eocene epoch (Paleocene)

The name "Tertiary" has entirely lost its original significance, but has, nevertheless, become thoroughly fixed in the literature of geology. In the early days of the science, the whole known geological column was divided into three groups of rocks, and later into four groups, namely: Primary, Secondary, Tertiary, and Quaternary. After the discovery of rocks still older than these, the term *Primary* was replaced by Paleozoic; *Secondary* by Mesozoic; while *Tertiary* and *Quaternary* have been retained as subdivisions of the Cenozoic.

Sir Charles Lyell first divided the Tertiary into Eocene, Miocene, and Pliocene on the basis of percentage of living species represented in each series, there being very few in the earliest and a very large percentage in the latest series. Later the Oligocene was added by combining some of the uppermost Eocene with some of the lowermost Miocene. The still later term "Paleocene" is used by some geologists to represent a separate epoch of the Cenozoic, and by others to indicate the earliest part of the Eocene epoch. The latter usage is preferred in this book.

The terms "Paleocene," "Eocene," "Oligocene," "Miocene," "Pliocene," and "Pleistocene," derived from the Greek language, literally indicate more and more recent epochs of the Cenozoic ("Recent life") era.

Because the terms "Tertiary" and "Quaternary" no longer have their original meanings, there have been some recent tendencies to do away with them entirely. Thus one author regards Eocene (or Paleocene) to Recent, inclusive, as "epochs" of the Cenozoic "Period," and another calls them "periods" of the Cenozoic "era," but such usages are confusing. It is much more satisfactory and less confusing to use "Tertiary" and "Quaternary" as "periods" of the Cenozoic "era" both because this is the common usage in the literature of geology, and because by far most writers of geological articles and books now so employ the terms.

The following table shows some of the principal subdivisions of the Cenozoic group of rocks in various representative parts of the United States:

		Atlantic Coastal Plain	Gulf Coastal Plain		Western Interior	Western California
			Alabama	Texas		
QUATERNARY	*Recent*	Surficial deposits	Surficial deposits		Surficial deposits	Surficial deposits Marine terraces
	Pleistocene	Columbia	Terrace deposits	Beaumont	(Glacial deposits)	Palos Verdes San Pedro Timms Pt. (Saugus)
UPPER TERTIARY	*Pliocene*	Brandywine Waccamaw	Citronelle (Missing)	Reynosa Lagarto	Blanco Republican River (Ricardo)	Tulare (Lomita) San Joaquin Etchigoin (San Diego) (Elsmere) Jacalitos (Repetto) Pico
	Miocene	Yorktown St. Marys Choptank Calvert (Missing) Trent Chesapeake	Pascagoula Hattiesburg Catahoula	Oakville	Santa Fe (Flaxville, Barstow) Loup Fork (Florissant) Arikaree	Santa Margarita Monterey San Pablo Temblor (Topanga) Vaqueros Modelo
LOWER TERTIARY	*Oligocene*	Vicksburg	Vicksburg	Frio	Monument Cr. White River John Day	Kreyenhagen Sespe
	Eocene	Castle Hayne Nanjemoy Aquia	Jackson Claiborne Wilcox		Uinta Bridger Green River Wasatch	Coldwater Tejon (restricted) Domengine Capay Meganos
	(Paleocene)	(Missing)	Midway		Fort Union (Raton)	Martinez

Distribution and Description of the Rocks

General Distribution. Tertiary strata appear at the surface in North America over the areas indicated on the accompanying map (Fig. 219). The important regions are the Atlantic and Gulf Coastal Plains, the West Indies, the Great Plains, and the great western (Cordilleran) region. In the western interior the numerous disconnected areas represent chiefly deposition in separate basins. On the Pacific Coast, Tertiary strata appear mostly as comparatively small, narrow belts because only the eroded edges of the usually upturned and folded rocks are visible in the mountains.

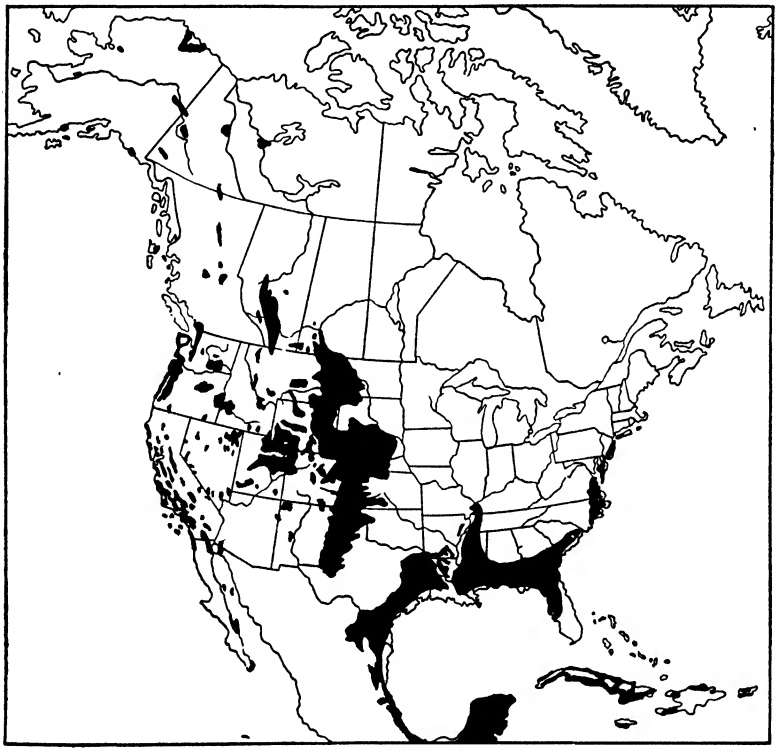


Fig. 219. Map showing the surface distribution (areas of outcrops) of Tertiary strata in North America. Tertiary volcanic rocks are separately shown on another map (Fig. 231).

Quaternary sediments comprising non-marine surface and near-surface deposits, and showing little or no consolidation, are widely scat-

tered over large parts of the continent. They include lake, stream, glacial, and wind-blown materials. The only marine deposits occur in places near the coasts.

Cenozoic volcanic rocks (largely Tertiary) cover vast areas of western North America (Fig. 231). Some small Tertiary intrusives also occur there.

Atlantic and Gulf Coastal Plains. *General Statement.* The Tertiary rocks of these regions are all of sedimentary origin. They are widely exposed, particularly in the Gulf Coastal Plain (Fig. 219). The Tertiary formations of the Atlantic Coastal Plain consist very largely of unconsolidated sands, gravels, clays, and marls. They are nearly all of marine origin, and generally very fossiliferous. Their maximum thickness is probably not more than 1000 feet. In the Gulf Coastal Plain both marine and non-marine deposits occur with the former predominant. The formations there are mainly sands or sandstones, clays or shales, marls or limestones, and some thick beds of lignite. The Cenozoic strata of the Gulf Coastal Plain commonly reach a thickness of several thousand feet. They are thickest in the southern Louisiana region where deep-well records and geophysical tests indicate a thickness of 20,000 to possibly 30,000 feet for the Cenozoic (largely Tertiary) sediments. A reasonable explanation of this great thickness is that contemporaneous rapid subsidence and deposition took place there during the growth of the Mississippi River delta.

Unconsolidated Quaternary deposits, consisting of both marine and non-marine sediments, conceal the Tertiary strata of the Coastal Plains in many places, especially near the coasts.

Eocene. Formations of Eocene age are excellently developed and widely exposed in the Coastal Plains from South Carolina to the southern tip of Texas. They are mainly marine sands, clays, and marls usually more or less consolidated. They range in thickness commonly from a few hundred to more than 1000 feet. Mention may be made of the important and extensive non-marine *Wilcox* formation of sands and clays with thick beds of lignite. Eocene formations only a few hundred feet thick are well exposed in a much smaller area from southern New Jersey into eastern Virginia.

Oligocene. Strata of this age, consisting of marine limestones and clays several hundred feet thick are well represented from South Carolina westward through the Gulf Coastal Plain to Texas.

Miocene. Miocene formations, largely marine sands, clays and marls,

are well exposed through the Atlantic Coastal Plain from central Florida to New Jersey, reaching a thickness of about 500 feet. In the Gulf Coastal Plain, Miocene formations, both marine and non-marine, are well developed and widespread. They are mainly sands (or sandstones) and clays reaching a maximum thickness of several thousand feet.

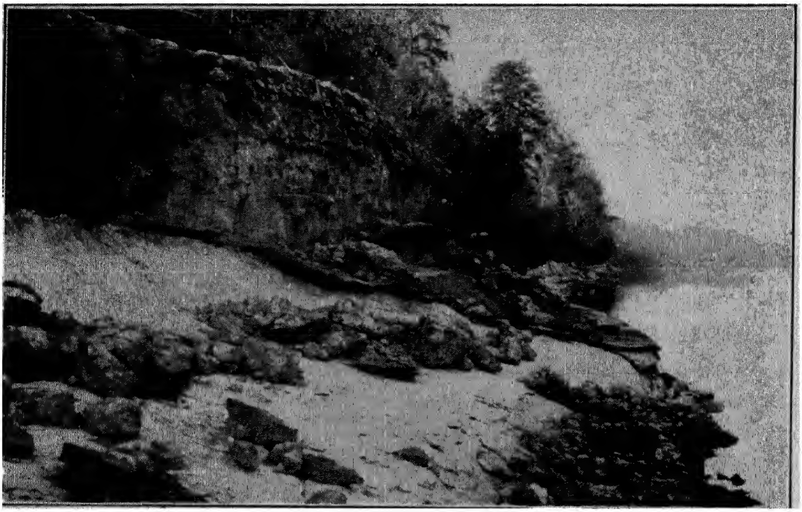


Fig. 220. Eocene sandstone resting by sharp contact upon Upper Cretaceous white chalk in Alabama. (After L. W. Stephenson, U. S. Geological Survey.)

Pliocene. Pliocene formations, consisting mainly of marine sands, gravels, clays, and marls, including Late Pliocene marine terrace deposits, occur in the seaward border of the Atlantic Coastal Plain where they are only a few hundred feet thick. Pliocene is represented across the southern Gulf Coastal Plain by marine sands and clays. A non-marine Upper Pliocene formation (*Citronelle*), mainly sand a few hundred feet thick, forms a wide belt completely across the southern part of the Gulf Coastal Plain. The concealed Pliocene thickens rapidly to thousands of feet under southern Louisiana.

Quaternary. Unconsolidated sediments of this age, including non-marine, marine, and beach materials, conceal the Tertiary strata in a wide belt facing the sea from eastern Long Island to the southern tip of Florida, and facing the Gulf of Mexico from Florida through Texas. These materials are often in the form of marine terraces.

Cenozoic of Florida. The Cenozoic formations underlying all or

nearly all of Florida deserve special mention. Surface exposures and well records indicate that the rocks are very largely limestones and marls, together with some Late Cenozoic clastic sediments. A large area of Lower Pliocene shell marl is exposed in southern Florida. The fact that these are all shallow-water marine deposits, reaching a thickness of fully a mile, proves that Florida was a sea-covered, slowly sinking region throughout nearly all of Cenozoic time.

Structure of the Rocks. The strata of both the Atlantic and Gulf Coastal Plains are almost entirely free from true folds, but some broad warps do occur. Most noteworthy is the previously mentioned downwarp or trough filled with a great thickness of sediment under southern Louisiana.

Faults of any consequence are almost entirely lacking in the Atlantic Coastal Plain, but a good many occur in the Gulf Coastal Plain. Most important is the Balcones fault zone in a general way marking the boundary between the Cretaceous and the Cenozoic strata of Texas where the Cenozoic portion of the Coastal Plain has been downfaulted as much as 1000 feet against the Cretaceous portion of Texas since Cretaceous time.

The Cenozoic formations of both Coastal Plains dip at low angles toward the tide water and thus successively older formations are encountered in passing inland from the shoreline.

Western Interior-Great Plains. *General Statement.* This vast region includes the Great Plains, the Rocky Mountains, the Colorado Plateau, the Basin and Range Province, and the Columbia Plateau (see Fig. 18). Cenozoic rocks, all of continental origin, occur in small and large areas in many places throughout this great region (Figs. 219 and 231). They comprise various kinds of materials such as lake, river, alluvial-fan, and wind-blown sediments, and great accumulations of volcanic rocks—both lavas and tuffs. Beds of imperfect (lignitic) coal also occur in various places. The following very brief descriptions of some of the best known formations will serve to give a fair idea of the nature of these rocks.

Eocene. Of the Eocene deposits, the oldest (Paleocene) is represented by the *Fort Union* formation consisting mainly of soft sandstones and shales (or clays), often with beds of lignitic coal. Its thickness ranges from less than 1000 feet to more than a mile. It is very widespread in the Great Plains of the northern United States and southern Canada. The *Wasatch* formation of variegated clays, shales, sandstones, conglomerates, and fresh-water limestones, with some coal beds,

ranges up to more than a mile thick. It forms the so-called "Pink Cliffs" of Utah, and beautifully colored and intricately eroded strata in Bryce Canyon, Utah (Fig. 221). It is extensively exposed in Wyoming and less so in northwestern Colorado. The *Green River* formation is a fresh-water lake deposit composed largely of evenly stratified soft shales (Fig. 222) which reach a thickness of 2000 feet. It is extensive in Wyoming and Utah both north and south of the Uinta Mountains. Many fossils, including fishes, insects, and plants,

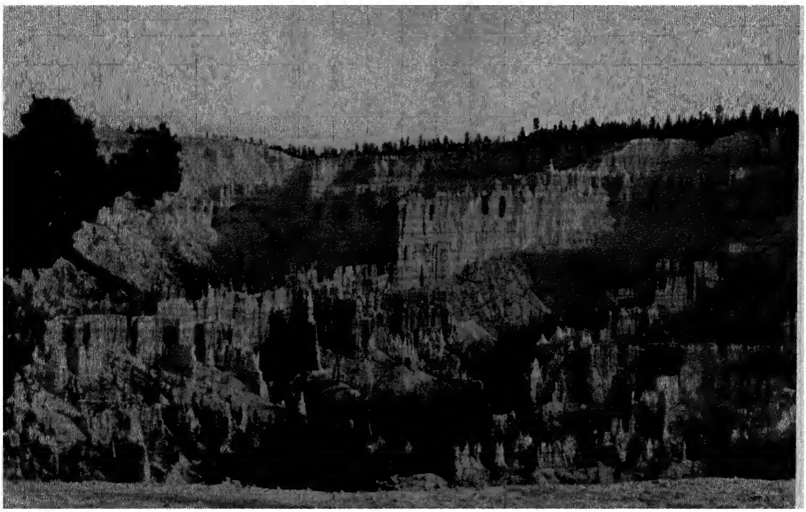


FIG. 221. Eocene (Wasatch) strata in Bryce Canyon, Utah. The vertically jointed, horizontal beds, 8500 feet above sea level, have been remarkably sculptured by weathering and erosion. The rocks are soft shales, limestones, and sandstones, beautifully colored.

occur in it. Next younger is the *Bridger* formation, hundreds of feet thick, consisting mainly of volcanic dust, together with some soft shales, etc. The materials were extensively deposited partly on land and partly in lakes both north and south of the Uinta Mountains. Youngest of the Eocene are the *Uinta* soft shales, sandstones, etc., chiefly of terrestrial (stream-deposit) origin and reaching a thickness of fully 1500 feet also both north and south of the Uinta Mountains. An example of the great Eocene volcanic deposits is the *San Juan* formation, consisting of tuffs piled up to a thickness of 3000 feet in southwestern Colorado. It is the lower part of a pile of Tertiary volcanics there 6000 to 7000 feet

thick. It is an interesting fact that the San Juan tuff rests upon an Early Eocene (*Telluride*) conglomerate of glacial origin.

Oligocene. Oligocene strata, well represented by the *White River* formation of moderate thickness, occupies extensive areas in Wyoming, western South Dakota, western Nebraska, and eastern Colorado. It comprises clays and soft sandstones, with some volcanic ash beds. Typical "Badlands" topography has often been developed in this formation.

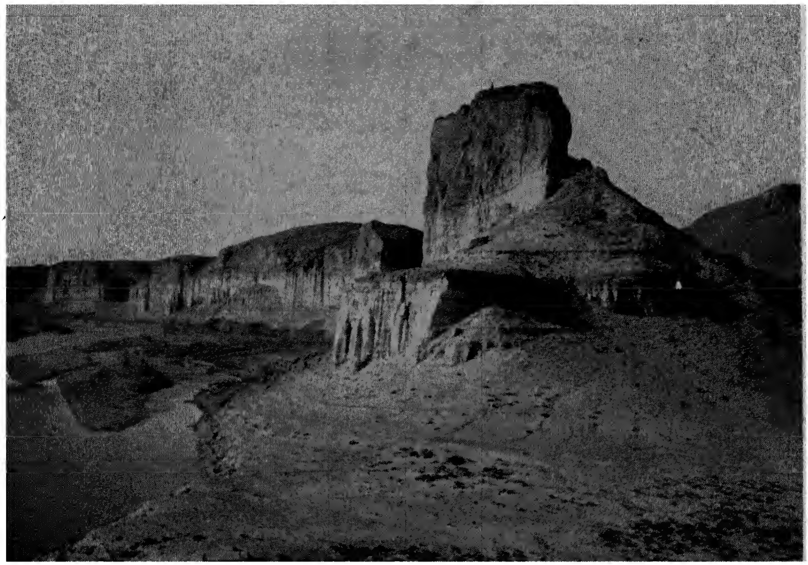


Fig. 222. The Green River formation of Eocene age as seen near Green River City, Wyoming. The well-bedded, nearly horizontal shales were laid down in a great fresh-water lake. (Photo by courtesy of the Union Pacific Railroad.)

The *Monument Creek* formation overlies the White River in the southern Great Plains.

The *John Day* formation of north-central Oregon is composed largely of volcanic ash beds, with some shale and lava beds—several thousand feet thick (Fig. 262). It is of Late Oligocene—Early Miocene age. Many fossil plants and mammals have been obtained from it.

Miocene and Pliocene. The Miocene, far less thick than the Eocene, is represented toward the base by the *Arikaree* formation of mainly soft sandstones extending widely from southern South Dakota

into western Texas; toward the middle by the *Florissant* beds which consist of laminated shales formed by deposition of fine volcanic dust in a small lake in Colorado, and remarkable for the great number of insect and plant remains in it, and the *Loup Fork* beds which form thin deposits of fine sands and marls (both subaerial and lacustrine) over extensive areas from South Dakota to Mexico; and at the top by the *Santa Fe* formation of continental origin in the southern Rockies.

Pliocene deposits formed in many parts of the western interior. They are of continental origin, probably with some lake beds. Thus

FIG. 223. "Toadstool Park": a view in the Badlands of western Nebraska. The rocks are of Oligocene age. (After Darton, U. S. Geological Survey.)

the *Ogallala* group of strata extends through much of Kansas, western Nebraska, and western Texas. Two important formations of this group are the *Republican River* in the north and the *Blanco* in the south. Miocene and Pliocene deposits comprise most of the extensively exposed Cenozoic in the central and southern Great Plains of the United States (Fig. 219).

Upper Tertiary tuffs and lavas, often interbedded with ordinary sediments, occur in many parts of the western interior. The Late Miocene and Early Pliocene *Barstow* and *Ricardo* (Red Rock Canyon) formations of the Mohave Desert in California, are good examples.

In addition to the Tertiary beds in the western interior (above described), there are also many small to large deposits, especially of Mio-

cene and Pliocene ages, in that part of the United States lying between the Rocky Mountains and the Sierra Nevada-Cascade Mountains. For most part these formations have not been carefully studied, though it is known that they represent all types of continental deposits.

Quaternary. Sediments of this age are very common throughout the western interior-Great Plains region. They include stream, lake, wind-blown, glacial, and alluvial-fan materials. In the Basin and

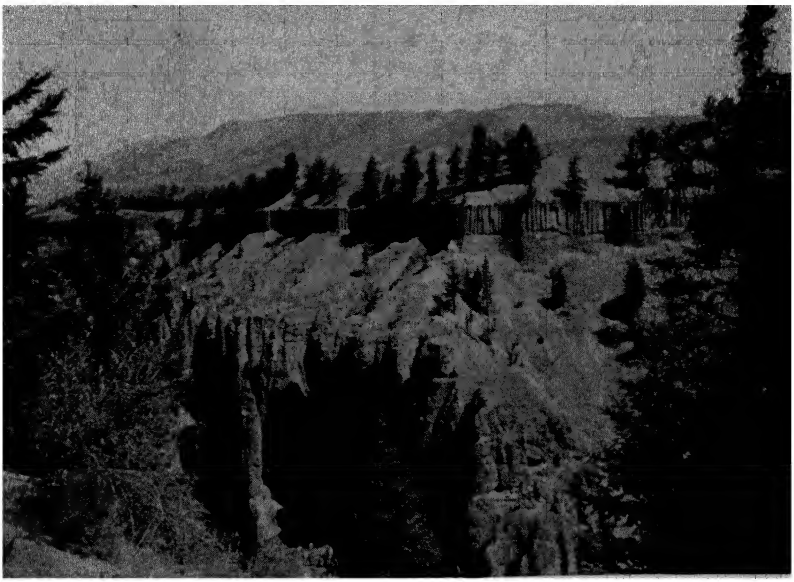


Fig. 224. Nearly horizontal beds of volcanic fragmental materials of Tertiary age, with an interbedded sheet of columnar lava toward the top. Near Tower Falls, Yellowstone National Park.

Range province, where they are especially important, they have usually been laid down in basins between the mountains. The Quaternary sediments are seldom more than slightly consolidated, and they are far thinner than the Tertiary strata, but thicknesses of 500 to 1000 feet are not uncommon.

Igneous Rocks. In the above descriptions, attention has been largely given to a consideration of the sedimentary rocks of the western interior-Great Plains, with some mention of tuffs and lavas, but igneous rocks of Cenozoic age are also of very great extent and importance in the western interior region (Fig. 231). Most extensive by far are the

FIG. 225. Beds of Tertiary, non-marine, soft shales (or clays) in Furnace Creek Canyon, near Death Valley, California. The upturned strata have been intricately eroded, giving rise to a "badlands" effect. The prevailing colors are yellow and red. (Photo by Willard.)

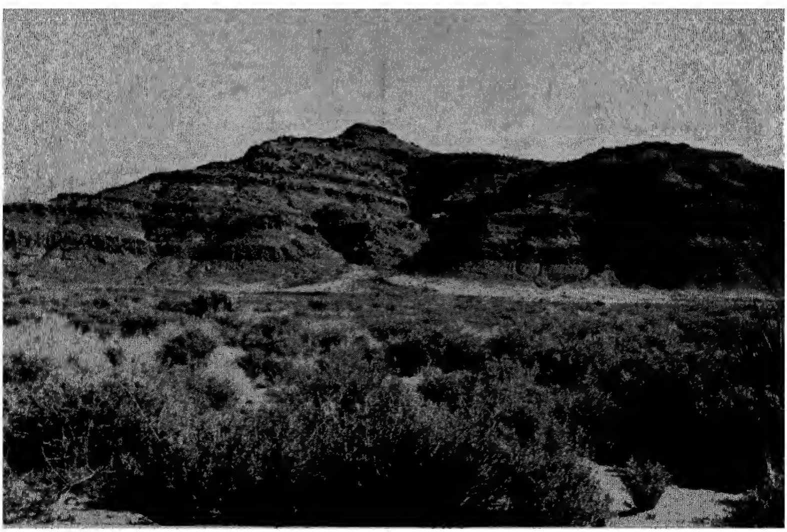


FIG. 226. Eight gently tilted Tertiary lava-flows separated by beds of volcanic fragmental materials. Thirteen miles south-southeast of Cima, Mohave Desert, California.

Tertiary volcanic rocks, but small bodies of intrusive rocks such as batholiths, laccoliths, and dikes also are known. Some Quaternary vol-

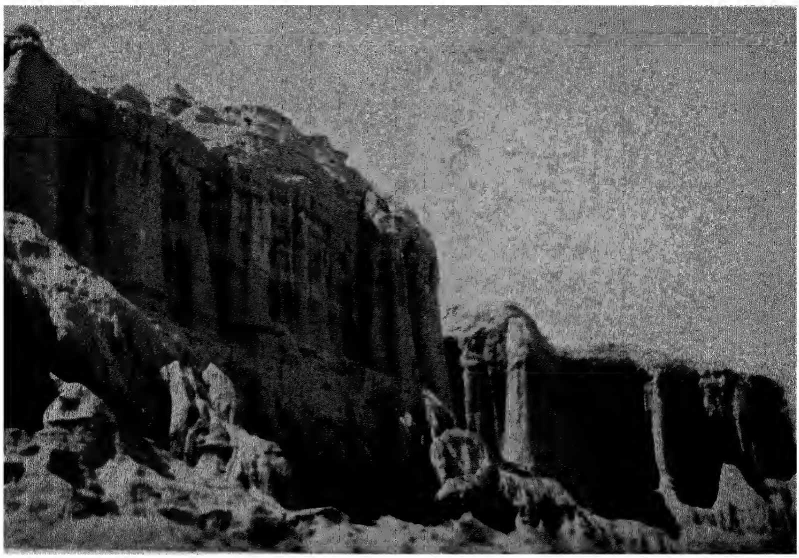


FIG. 227. Soft volcanic tuff and shaly sandstone of Late Tertiary age in Red Rock Canyon north of Mojave, California. The cliff, about 200 feet high, is remarkably sculptured by rain-wash.

canic rocks occur here and there. The Cenozoic igneous activity of the region is discussed beyond.

Structure of the Rocks. The structure of the Cenozoic strata of

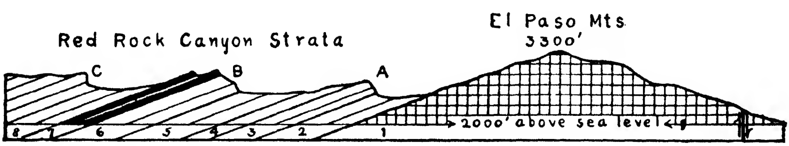


FIG. 228. A generalized west-northwest structure section through Red Rock Canyon north of Mojave, California. Vertical scale exaggerated. Length of section, 3 miles. The Red Rock Canyon strata of Late Tertiary age are fully 2500 feet thick. They consist mainly of bedded volcanic tuffs, sandy and shaly beds, and some sheets of lava (black bands). They rest unconformably upon the granite of the El Paso Mountains. (After W. J. Miller, "Jour. of Geog.," Vol. 25, 1926, p. 332.)

the Great Plains is simple. There is very little folding or faulting, and the various formations nearly everywhere show a gentle eastward dip.

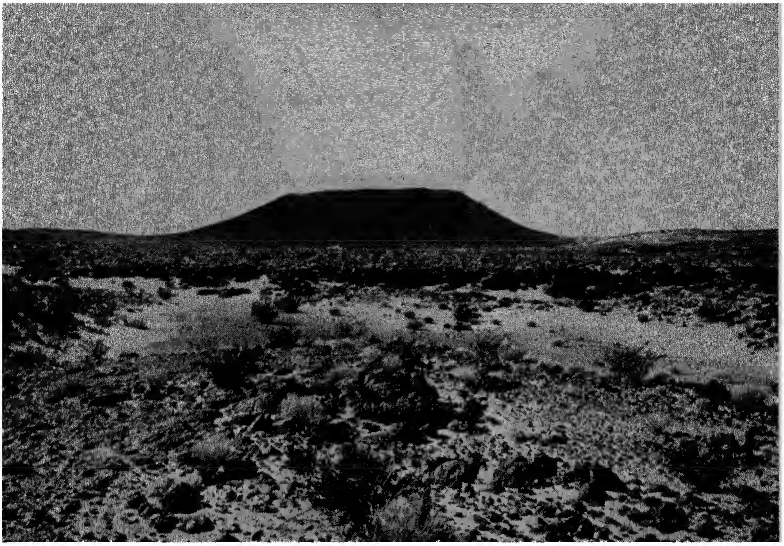


FIG. 229. A recent cinder cone on the Mohave Desert near Amboy, California.

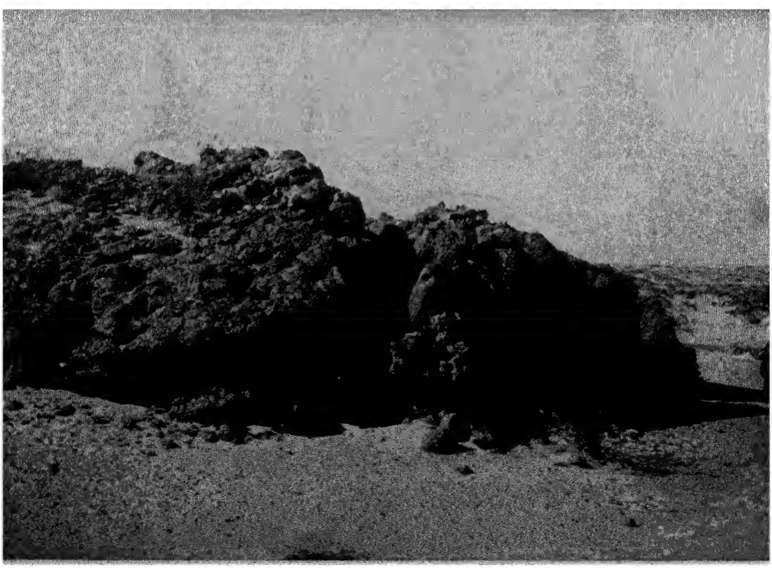


FIG. 230. An edge of a recent lava flow on the Mohave Desert near Amboy, California. This flow is associated with the cone shown in Fig. 229.

In the Rocky Mountains the Cenozoic rocks, particularly the older formations, have often been disturbed by faulting and some tilting, but in many areas (often extensive) they still lie in their original horizontal positions.

Between the Rocky Mountains and the Sierra-Cascade Mountains, Cenozoic rocks—both sedimentary and volcanic—have often been locally

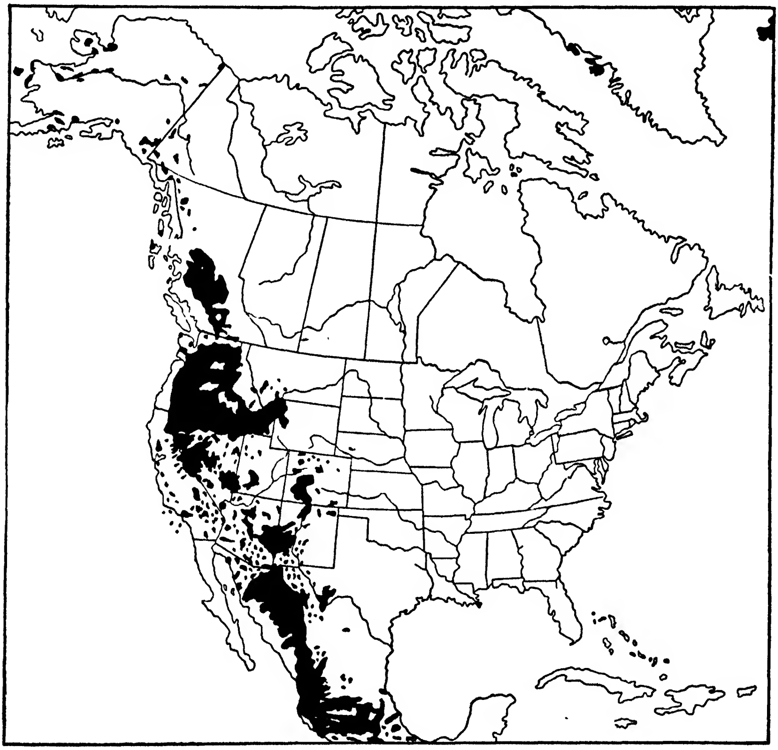


FIG. 231. Map showing the surface distribution (areas of outcrops) of Cenozoic volcanic rocks in North America. (Principal data from the U. S. Geological Survey.)

disturbed by some folding, as in the Columbia Plateau (Fig. 232); or by tilting (Fig. 233); or often by faulting, as in the Basin and Range Province.

Pacific Coast. *Eocene.* Eocene strata are prominently developed in western California, Oregon, and Washington, and in Alaska. They are mainly of marine and brackish-water origin, reaching thicknesses

of 8000 to 12,000 feet. They are chiefly sandstones, conglomerates, and shales, but with locally developed lavas, tuffs, impure limestones, and diatomaceous shales. Some Eocene beds of the Pacific Coast are of fresh-water origin with beds of more or less commercial coal and lignitic coal.

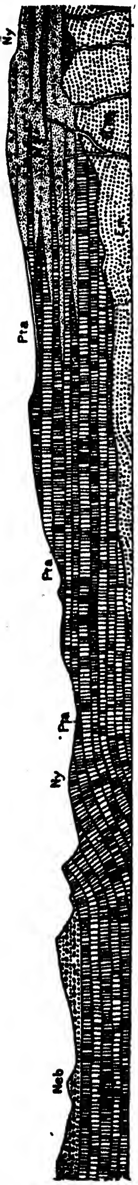


FIG. 232. Structure section in central Washington showing sheets of Miocene lava piled up to a thickness of fully a mile. Length of section 11 miles. *Em*, Eocene sandstone; *Ny*, Miocene lava (basalt); *Neb*, Miocene strata; *Pta*, Pleistocene lava. Note the distinct fold in the lava. (After G. O. Smith and Calkins, U. S. Geological Survey, Folio 86.)

Probably the finest development of marine Eocene strata in North America is that of the Coast Range of California. Six formations (see table on page 315) there constitute a practically complete Eocene section. All of these formations are more or less fossiliferous. In the Ventura region of southern California the Eocene is 12,000 feet thick. Figure 235 shows extensively upturned strata of this age.

Oligocene. Strata of this age are much less widely distributed than the Eocene. The deposits are mostly sandstones and shales in western Oregon and Washington, and in middle-western California (*Kreyenhagen* formation). In southwestern California the *Sespe* formation is a non-marine red sandstone 4000 to 6000 feet thick. Recent studies have shown that the Sespe ranges in age from later Eocene to earlier Miocene.

Miocene. Marine strata of this age are about as prominently developed on the Pacific Coast as the Eocene, the beds being very largely sandstones and shales, often with much diatomaceous shale in the Upper Miocene (Fig. 237). In California the Lower Miocene formations—*Vaqueros* and *Temblor* (*Topanga*)—are often separated from the Upper Miocene—*Monterey* (*Modelo*)—by an unconformity, as for example in the Santa Monica Mountains of southern California. Volcanic and dike rocks are common in the Middle Miocene of southern California. Miocene strata in California reach thicknesses of 15,000 to 20,000 feet, the *Topanga* and *Modelo* formations each showing a thickness of about

7000 feet in western Los Angeles. Various Miocene beds in southern California are rich in oil. Miocene is also well developed on the Pacific border of Alaska.

Pliocene. Pliocene marine strata are less extensively developed on the Pacific Coast than the Miocene, the principal areas being in California in the Coast Range Mountains, the southern part of the Great Valley, the southwestern border of the state, and the Imperial Valley in the south. Several small areas are on the coasts of Oregon and

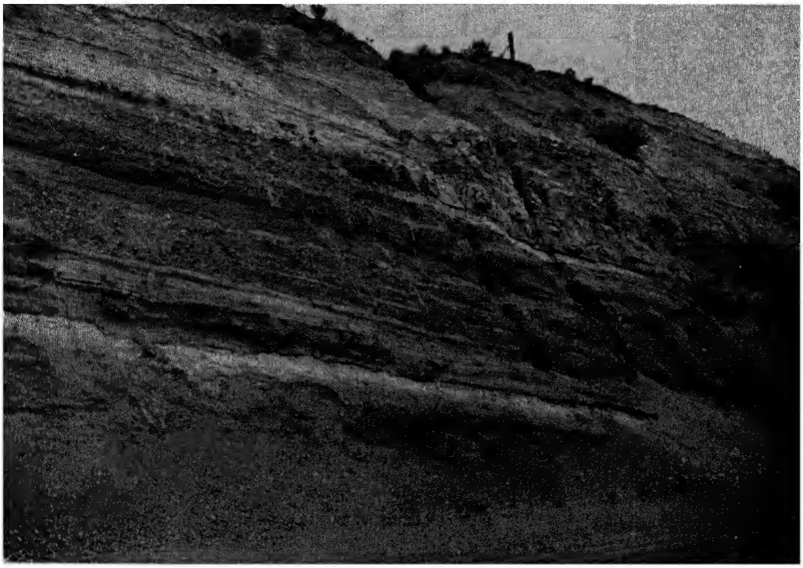


FIG. 233. Gently tilted Tertiary lake beds about 10 miles southeast of Unity, Oregon. They are slightly consolidated sands, gravels, and clays, with a bed of white diatomite near the bottom, and a bed of volcanic ash near the middle.

Washington. The marine Pliocene reaches thicknesses of 4000 to 5000 feet near San Francisco, and 10,000 to 20,000 feet in the Los Angeles-Ventura region. In California the marine Pliocene is well represented in stratigraphic succession by several formations listed in the table on page 315. These consist very largely of sandstones, conglomerates, and shales. In the Los Angeles region the Middle and Upper Pliocene are known as the *Pico* formation. Great quantities of oil are obtained from the southern California Pliocene.

Pliocene volcanic rocks are common in the San Francisco Bay region and northward for some distance.

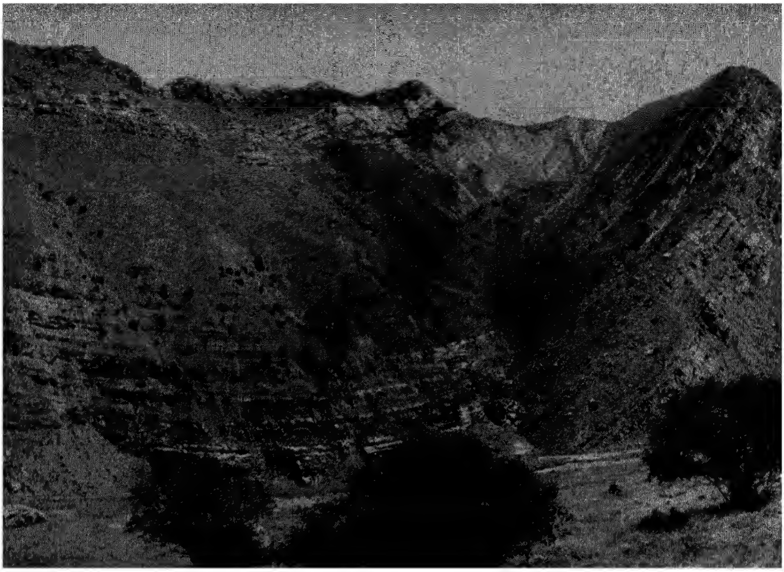


FIG. 234. Part of a syncline showing earlier Tertiary marine strata. Prominently outcropping beds toward the lower and right sides of the syncline are Upper Eocene; the boldly outcropping beds (lighter colored) next above are Oligocene; and at the top there is some Miocene. San Emigdio Canyon, south of Bakersfield, California. (After R. Anderson, U. S. Geological Survey, Bul. 471.)

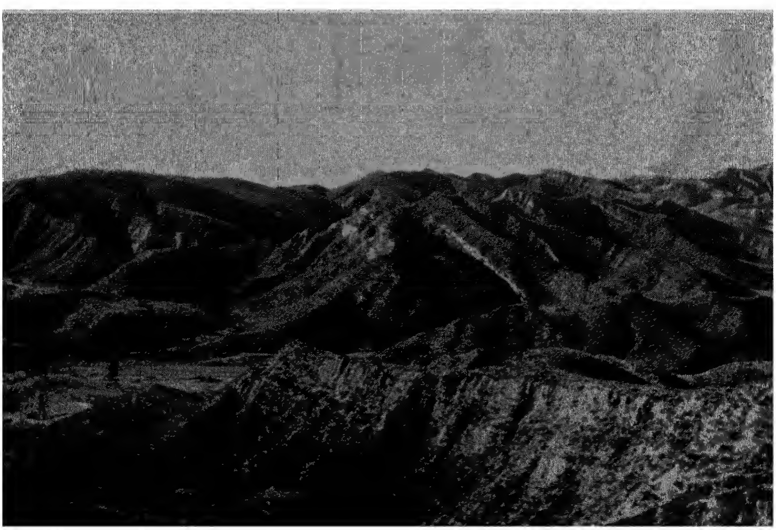


FIG. 235. Strongly upturned marine Eocene strata. Simi Valley in southern California. (Photo by F. B. Tolman and U. S. Grant, IV.)

FIG. 236. Nearly white, gently dipping Miocene (Modelo) shale on Mulholland Drive, Los Angeles, California. Fossil fishes, plants, and pelecypods occur at this locality.

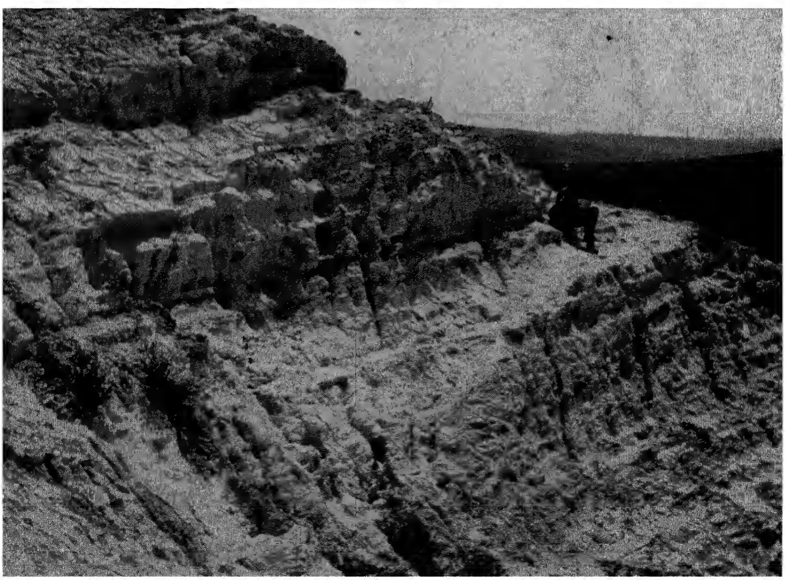


FIG. 237. Soft white diatomite of Miocene age in Santa Barbara County, California. (After Arnold, U. S. Geological Survey, Bul. 322.)

Pliocene non-marine sediments are widely developed in many parts of the Pacific Coast, especially in the Great Valley of California where the fresh-water *Tulare* formation (partly Pliocene) is a good example.

Quaternary. Sediments of this age are found in many parts of the Pacific Coast of the United States mainly in the form of marine and non-marine terrace, beach, and continental deposits, but there are also some regular marine formations of considerable thickness. The last

FIG. 238. A detail view of faulted Pliocene (Pico) strata. The dark beds are rich in oxidized petroleum. Five miles northwest of San Fernando, California.

named are best known in the Los Angeles-Ventura region of southwestern California where the marine beds are represented by various formations (see table on page 315). Of these the Lower Quaternary *Saugus* is partly marine and partly non-marine. The total thickness of these formations is usually from a few hundred to a few thousand feet. The formations are mainly sands, clays, and gravels, in part moderately consolidated.

Quaternary continental deposits of stream, lake, and alluvial-fan origin are more widespread than the marine deposits. These generally unconsolidated materials usually occupy valleys between the mountains and ridges, as for example on a grand scale in the Great Valley of

California. Not uncommonly their thickness ranges from 500 to 1000 feet or more. In many places their accumulation is still in progress.

Igneous Rocks. Cenozoic volcanic and dike rocks are found in most parts of the Pacific Coast. Probably every epoch of the Cenozoic is represented by them. Particularly important are the great Tertiary volcanic formations of the Cascade Mountains and the northern Sierra Nevada Mountains; the Eocene lavas of western Washington and Ore-

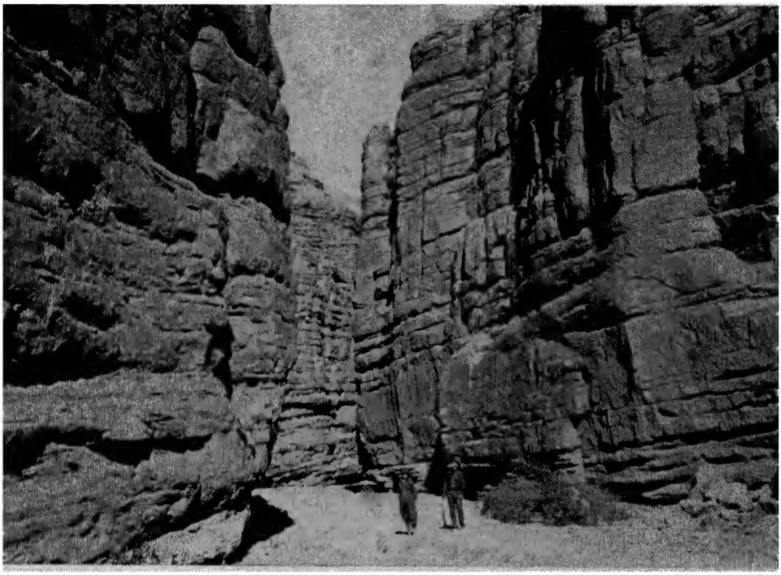


FIG. 239. Nearly horizontal beds of non-marine, red sandstone of Late Tertiary age. Painted Canyon, east of Mecca, California.

gon; and the Miocene and Pliocene lavas in the southern and northern Coast Range Mountains, respectively, in California.

Pleistocene, and even Recent, volcanics occur in the Cascade-Sierra region, but they are much less common than those of Tertiary age. The igneous activity of the Pacific Coast is discussed beyond.

Structure of the Rocks. In the Coast Range Mountains of California, Oregon, and Washington, the Tertiary rocks are generally more or less strongly folded and cut by many faults both large and small (Figs. 241, 242). The most important structure is the great San Andreas fault which extends through nearly the whole length of the California Coast Ranges and continues southward to the Gulf of California. Both normal and high-angle thrust faults are common. The Tertiary

strata underlying most of the Great Valley of California are usually only moderately folded (Fig. 243).

The earlier Quaternary deposits are often in a highly disturbed condition, but the later ones are seldom very notably deformed except by some Recent fault movements.

Physical History

General Relations of Sea and Land. In the interest of more clearly presenting an outline of our unusually detailed knowledge of

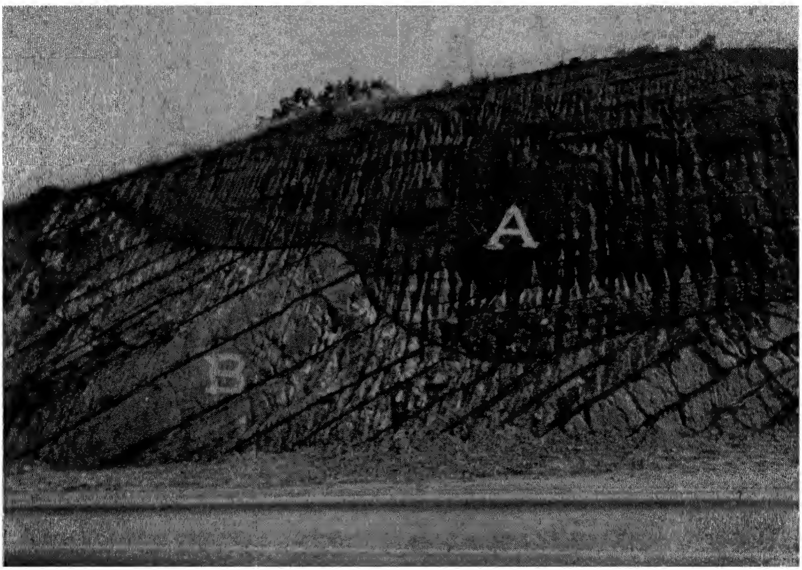


Fig. 240. **Nearly horizontal beds of slightly consolidated, brown alluvium (*A*)** of Late Quaternary age resting by unconformity upon strongly tilted beds of marine sandstone and shale (*B*) of Miocene age. Campus of University of California at Los Angeles.

the complicated physical history (excluding the Ice Age) of North America during the present (Cenozoic) era, we shall depart somewhat from our usual method of presentation by considering first the general relations of sea and land, and then the Cenozoic history of each important physical province of the continent, first in the east and then in the west.

The general relations of sea and land during Tertiary time are graphically shown by the accompanying paleogeographic maps (Figs.

244-247). During Paleozoic time epeiric seas spread over, and disappeared from, extensive parts of North America many times. Such

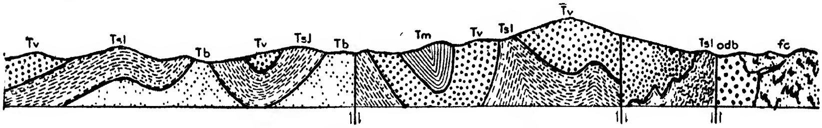


FIG. 241. Structure section across a portion of the Coast Range Mountains of central-western California, showing the nature of the Pleistocene folding and faulting. Length of section, 9 miles. *fc,* Jurassic? rocks; *odb,* pre-Tertiary intrusive rock; *Tb, Tsl,* Oligocene sandstone and shale; *Tv, Tm,* Miocene sandstone and shale. The profound fault at the right is the one along which renewed displacement occurred to cause the San Francisco earthquake of 1906. (After Branner, Newsom and Arnold, U. S. Geological Survey, Folio 163.)

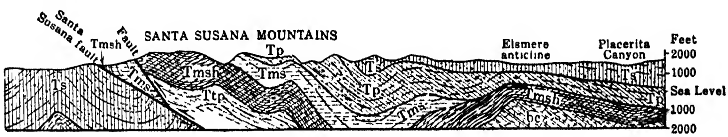


FIG. 242. A nearly north-south structure section through a part of western Los Angeles County, California, proving that the region was strongly folded and faulted after Early Pleistocene (Saugus) strata were deposited. Length of section, 6.5 miles. Symbols: *bc* = pre-Cretaceous crystalline rocks; *Ttp* = Miocene (Topanga) sandstone; *Tmsh, Tms* = Miocene (Modelo) shale and sandstone; *Tp* = Late Pliocene (Pico) sandstone; and *Ts* = Early Pleistocene (Saugus) sandstone. (After W. S. Kew, U. S. Geological Survey, Bul. 753.)

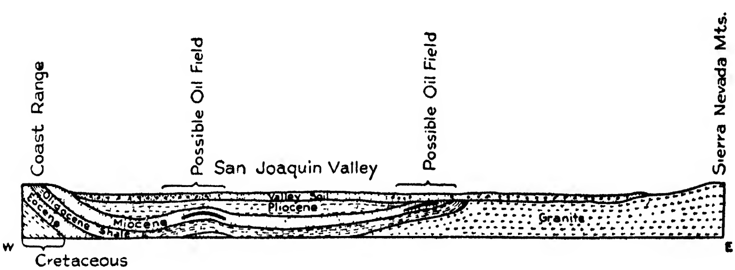


FIG. 243. A generalized structure section across the San Joaquin Valley part of the Great Valley of California showing the positions and structure of the Cenozoic deposits and their relations to the older rocks. The granite is Late Jurassic. The "Valley soil" is mainly Quaternary, unconsolidated alluvium which was carried down by streams from the mountains on either side and spread over the valley floor. (After California Division of Mines.)

seas were far less common in the Mesozoic era, the most important having been the great western sea which cut the continent in two in Late Cretaceous time. During the Tertiary period none of the still

more restricted epeiric seas ever cut across the continent, or even extended very far into it. As a matter of fact, sea water spread over less of the continent during the Tertiary period than at the present time.

In Eocene time (Fig. 244) much of the Gulf Coastal Plain of the United States; all of Florida; and parts of the southern and northern

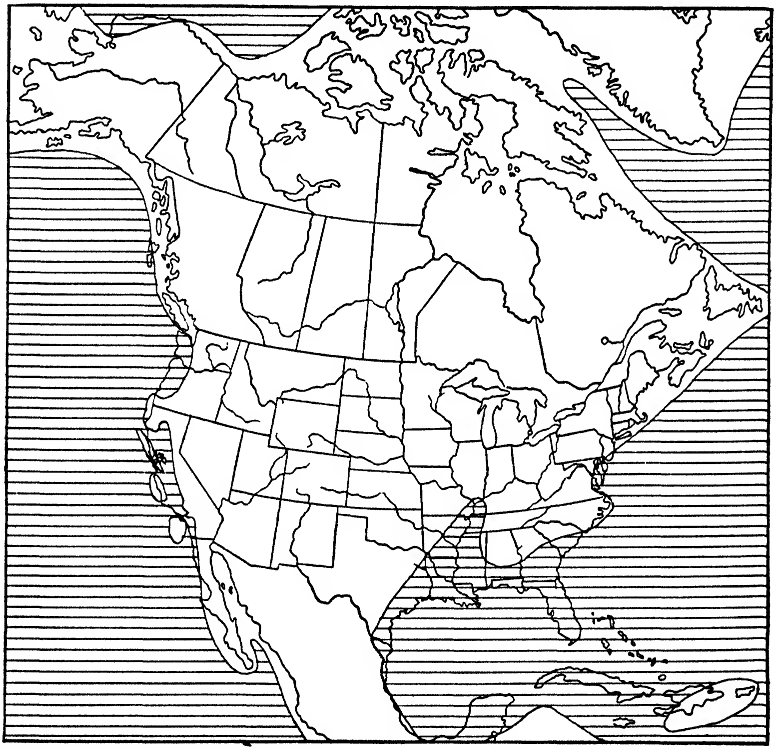


FIG. 244. Generalized paleogeographic map showing sea and land relations in North America during Eocene time. White areas, land; ruled areas, sea. Principal data (modified) after B. Willis, C. Schuchert, and F. Tolman.

Atlantic Coastal Plains were under the sea most of the time. In the west much of the western one-half of California; considerable parts of western Oregon and Washington; very little of western Canada; and some of northern Alaska were sea-covered most of the time.

Oligocene time was marked by notably restricted seas which covered only the eastern Gulf Coast and Florida, and three small embayments on the Pacific Coast as shown by Figure 245.

During the Miocene epoch the marginal seas were again generally more extensive, particularly over most of the Atlantic Coastal Plain and much of western California as shown by Figure 246.

The Pliocene marginal seas were very restricted with submergence only of small parts of the Atlantic, Gulf, and Pacific Coasts as shown by Figure 247. At this time, however, the Gulf of California extended

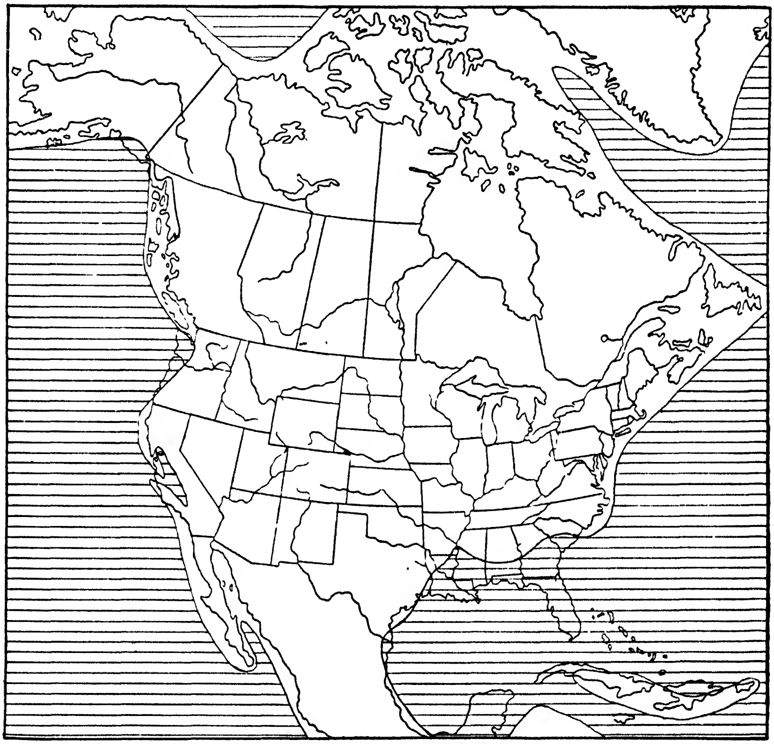


FIG. 245. Generalized paleogeographic map showing sea and land relations in North America during Oligocene time. White areas, land; ruled areas, sea. Principal data (modified) after B. Willis, C. Schuchert, and R. Reed.

farther north than today, and there seems to have been a seaway connecting the Arctic and Atlantic Oceans across the Arctic Islands region.

Early in the Quaternary period, the marginal seas were of very slight extent—much less even than in the Pliocene. During most of the period, North America seems to have been both broader and generally higher, relative to sea level, than it is today, with land extending out over the continental shelf areas. The remarkable submarine canyons

now occurring on both sides of the continent were then quite likely cut by rivers on the margins of the higher and more extensive continent. At the same time the level of the sea no doubt stood several hundred feet lower than now because so much water from the sea was transferred to the lands in the form of the great ice sheets which covered many millions of square miles of land.

FIG. 246. Generalized paleogeographic map showing the relations of sea and land in North America during later Miocene time. White areas, land; ruled areas, sea. Principal data (modified) after B. Willis and R. Reed.

In Late Quaternary time, possibly because of the great weight of the glaciers, the continent became notably depressed. The continental-shelf areas, with their newly cut canyons, became submerged, and sea water also spread over parts of the continent much more extensively than at any other time during the Cenozoic era. Hudson Bay was then formed; much of the Arctic Islands region was submerged; the Gulf of St. Lawrence was formed; the coasts of southern Alaska, British

Columbia, and southern California were then partly submerged, in each case leaving off-shore islands, many of which have existed to the present time. San Francisco Bay and Puget Sound were then formed by subsidence.

During still later (Recent) time, much of North America, especially its northeastern one-quarter, has been partially and unequally re-elevated, but it is still far below its earlier Quaternary general height.

FIG. 247. Generalized paleogeographic map showing the relations of sea and land in North America during Pliocene time. White areas, land; ruled areas, sea. Principal data (modified) after C. Schuchert and R. Reed.

Eastern North America. *Atlantic Coastal Plain.* During most of Eocene and Oligocene times, much of the southern Atlantic Coastal Plain and Florida were occupied by sea water (Figs. 244, 245), while the middle part of the coastal region was land. Part of the northern Atlantic Coastal Plain was sea covered in the Eocene, but it was all land in the Oligocene. During Eocene time the newly added belt of Cre-

taceous deposits lay along the shore, and the Eocene strata are known to have been derived mostly from the Cretaceous, and in part from the more inland older formations.

Much of the Atlantic Coastal Plain region and Florida were submerged during most of Miocene time (Fig. 246).

During the Pliocene epoch only parts of the seaward edge of the Atlantic Coastal Plain and the eastern one-half of Florida were submerged, the Late Pliocene being represented by the *Brandywine* marine-terrace deposits now lying a few hundred feet above sea level.

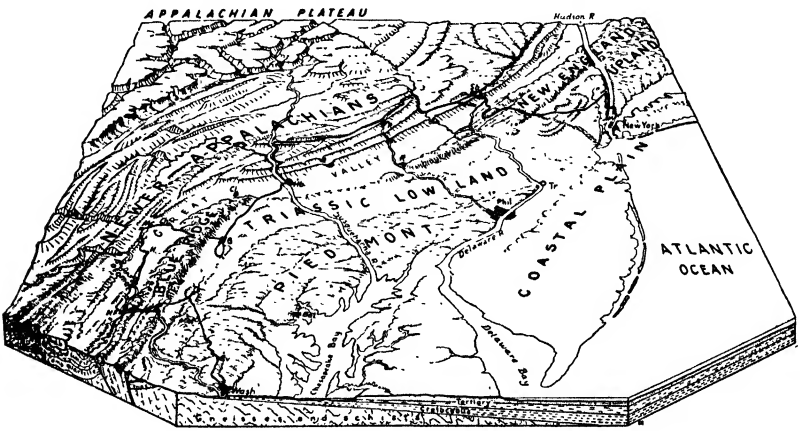


FIG. 248. Block diagram showing the topographic features and relations of the northern Appalachian and northern Atlantic Coastal Plain regions, and the structures of the underlying rocks. The gneisses and schists are pre-Paleozoic in age. Note the gently dipping Cretaceous and Tertiary strata underlying the Coastal Plain. Also note how the superimposed Potomac, Susquehanna, Delaware, and Hudson Rivers cut across the ridges and the geologic structures. The heavy line indicates the route of a geological excursion. (From International Geological Congress Guidebook No. 7. Drawn by E. J. Raiz.)

During the Quaternary period a series of unconsolidated marine deposits, comprised under the name *Columbia,* were laid down on the outer part of the coastal plain area. Like the Brandywine formation, the Columbia consists wholly of surficial materials, but at lower altitudes. In the north the Columbia is rather clearly divisible into five or six parts including the *Sunderland, Wicomico, Talbot,* and *Pamlico.* Each of these is represented topographically by a more or less distinct terrace, the oldest being at the highest level. Each of the terraces was caused by submergence below sea level and deposition of sediments, followed by emergence and erosion.

The modern shoreline has developed in detail during the present (Recent) epoch.

Gulf Coastal Plain. During Eocene time extensive sedimentation took place over much of the Gulf Coastal Plain region (Fig. 244). An embayment of the Gulf extended northward in the Mississippi River region, as far as Illinois much as it did in the Late Cretaceous. An unconformity between the Cretaceous and Eocene clearly shows that there was a transgression of the Eocene sea over the area. Marine conditions in this embayment were, however, more or less interrupted by considerable development of non-marine deposits such as lignite beds.

Oligocene conditions were a good deal like those of the Eocene, but the Mississippi embayment was much less pronounced and very little of the coast of Texas was then submerged (Fig. 245).

During Miocene time the Mississippi embayment was gone as such, but sea water spread over the southern part of the Gulf Coast most of the time (Fig. 246).

In the Early Pliocene much of the southern Gulf Coastal Plain region was submerged. Later in the epoch the whole southern Gulf Coastal Plain region was covered with a non-marine (Citronelle) formation.

Some marine sediments were laid down along the margin of the Gulf Coast during Quaternary time, and late in the period (Recent epoch) the present shoreline became established.

Eastern Highland Region. Mention has already been made (pp. 268, 270, 271) of the facts that an old age-peneplain surface, extending through the eastern highland region from central Alabama to the Gulf of St. Lawrence, was mantled in part with alluvial deposits and in part with Late Cretaceous marine sediments; that this region was upwarped at the close of the Cretaceous period; and that many streams flowed down the flanks or slopes of the great elongate upwarp first cutting their way through the mantle of alluvial and marine deposits and then into the underlying rocks, during Early Tertiary time, thus causing them to become superimposed streams.

By about Middle Tertiary time, the eastern highland region was once more reduced to an old age-peneplain surface known in part as the Schooley peneplain (Fig. 250A).

In still later Tertiary time, this old erosion surface was upwarped unevenly in amounts usually ranging from a few hundred feet to a few thousand feet. This was an event of prime importance in the Cenozoic history of the eastern United States because it was the first step in the

development of most of the existing relief features of the whole eastern highland region, these features having been produced largely by stream dissection of that upraised surface. All the valleys, great and small, such as the Champlain, Connecticut, Mohawk, Hudson Valleys, and the numerous valleys in the Appalachian region, have been produced since the uplift of the worn-down Middle Tertiary surface. Many remnants of the peneplain surface still remain. In the southern Appalachians (e.g. the Great Smoky Mountains), New England, and the Adirondack Mountains of New York, parts of the regions are composed of very resistant plutonic and metamorphic rocks, and hence they were not reduced to a stage beyond that of early old age or late maturity.

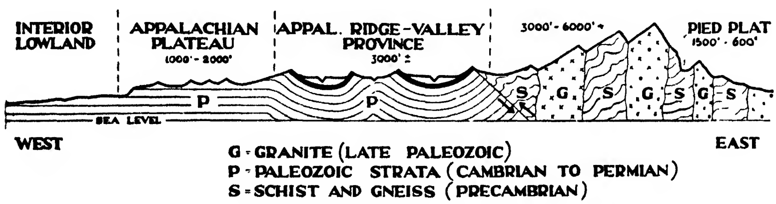


FIG. 249. This highly generalized profile and structure section shows the topographic and geologic relations of the various provinces of the southern Appalachian region. The highest part represents the Great Smoky Mountains of the Blue Ridge Province. These mountains were not peneplaned by Middle Tertiary time. The vertical scale is greatly exaggerated.

These resistant rocks, then forming both monadnocks and larger masses, still stand out conspicuously above the re-elevated old erosion surface (Fig. 249).

The later Tertiary uplift of the peneplain revived the power of the formerly sluggish streams so that they again became very active agents of erosion. Certain of the important streams such as the Susquehanna, Potomac, Delaware, and Hudson, which became superimposed during Early Tertiary time, continued as such during the later Tertiary uplift and to the present time. Thus the Susquehanna cuts across a whole succession of ridges in the Appalachian "Ridge and Valley" Province while, in accordance with the same explanation, the Delaware cuts through the Kittatinny ridge at the famous Delaware Water Gap (Fig. 250). The lower Hudson pursues a course no less out of harmony with the country through which it passes. It flows at a considerable angle across the folded structures above the Highlands, after which it passes through a deep gorge which it has cut through the hard granites and other rocks of the Highlands.

While the superimposed streams were cutting deep trenches across hard and soft rock alike, numerous side streams or tributaries came into existence and naturally developed along the belts of weak rock and in harmony with the geologic structures. This principle is especially well illustrated by all of the streams now occupying the valleys between the Appalachian ridges (Fig. 248). At the same time the ridges developed along the belts of hard rock, their summits representing portions of the old (Schooley) peneplain surface (Fig. 250). These ridges all rise to the same general level for miles around, and as viewed from the summit of any one of them, the concordant altitudes give rise to what is called the "even sky-line," which is a most striking feature of the land-

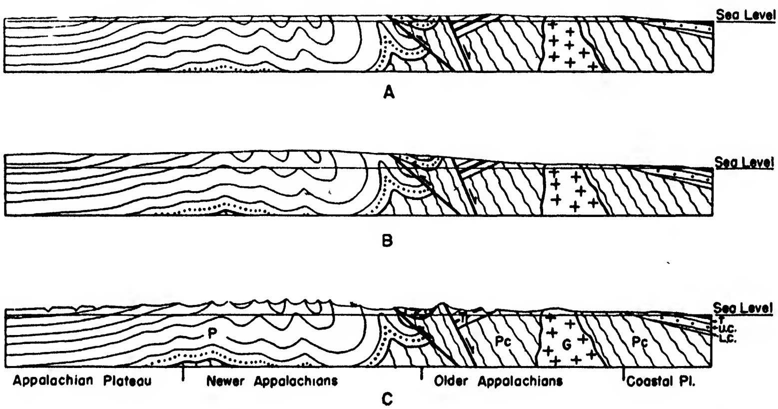


FIG. 250. Highly generalized structure sections across the Eastern Highland (Appalachian) region, from the Chesapeake Bay vicinity to southwestern Pennsylvania, showing the Cenozoic history. Pc = pre-Cambrian metamorphic rocks; G = pre-Cambrian intrusive; P = Paleozoic strata; Tr = Triassic rocks; L.C. = Lower Cretaceous; U.C. = Upper Cretaceous; and T = Tertiary.

Section A, the Middle or late Middle Tertiary Schooley peneplain which was produced after the close of Cretaceous time.

Section B, the upwarped Schooley peneplain on which a new cycle of erosion began and resulted in the later Tertiary partial peneplanation (Harrisburg peneplain).

Section C, present-day conditions. The ridge tops are remnants of the Schooley peneplain, and the wide valley floors represent the Late Tertiary Harrisburg partial peneplain. Minor effects of two still later dissections are not shown.

scape (Fig. 248). In northern New York and southern New England remnants of the upraised peneplain surface are also distinctly shown, but the "ridge and valley" topography was not so conspicuously developed there because of the less favorable nature and structure of the rocks

(largely igneous and metamorphic). Remnants of the uplifted peneplain surface are also well-preserved in the Appalachian Plateau, but, because the strata are there nearly horizontal, lack of structural control has there given rise to an irregular (often "dendritic") drainage pattern.

After the uplift of the peneplain, the larger streams cut down their channels most rapidly and were the first to reach "grade," that is a condition in which, because of low velocity, they could no longer cut down their channels, though the widening process could continue because of lateral erosion by the meandering streams. The commonly occurring broad-bottomed, stream-cut valleys, in the area under discussion, show that many of the streams had reached graded, or nearly graded, condition before the close of the Tertiary (Figs. 249, 250). The erosional surface represented by these valley floors has been called the Harrisburg

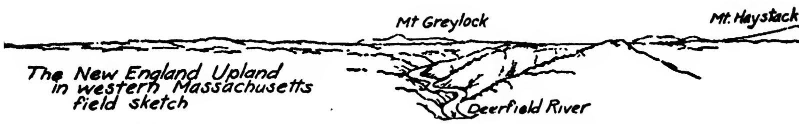


FIG. 251. Sketch showing part of the New England uplifted Middle Tertiary peneplain at an altitude of about 1400 feet. Two monadnocks rise above the surface, and the Deerfield River has deeply trenched it. (Drawn by A. K. Lobeck.)

peneplain. In the northern Appalachian district, at least, we have evidence to show that after the larger streams reached grade there was an appreciable renewed uplift of the land which again revived the activity of the streams. Thus the broad Hudson Valley, with minor hills rising above its surface, was produced when the Hudson was well along toward a graded condition and then, as a result of this Late Tertiary uplift of the land, the present narrow and fairly deep inner valley of the Hudson was formed. The Hudson did not reach grade in this inner valley, its work having been interrupted by both the subsidence of the land and the spreading of the great ice sheet over the region.

This inner valley of the Hudson has been traced for fully 100 miles eastward beyond the mouth of the present river. The Coast and Geodetic Survey has made a detailed map of the ocean bottom near New York City, and the submerged valley of the Hudson River is clearly shown as a distinct trench cut into the continental shelf. Even in the Hudson Valley above New York City, the narrow inner valley has a depth of hundreds of feet and is mostly submerged below tide water. Without question, this submerged Hudson Valley was cut when

the region was land, and thus we have positive proof that, late in the Tertiary and possibly extending into the Early Pleistocene, the region of southeastern New York was notably higher than it is today. Conservative estimates place the amount of elevation greater then than now at not less than 1000 feet because the end of the Hudson channel is submerged fully that much. The coast was then at what is now the edge of the continental shelf or platform about 100 miles east of the present coast line. That this greater altitude was well before the close of the Ice Age is proved by the fact that the inner Hudson Valley now contains much glacial debris. By similar reasoning, based upon the drowned valleys of the Maine Coast and the lower St. Lawrence, we know that those seaboard regions were also notably higher then than now.

During later Pleistocene time, the northern part of the Eastern Highland Region, including New York and New England, subsided (possibly because of the weight of the glacial ice upon it) so that by the close of the epoch, and shortly after, the land was relatively lower even than it is today. It was during part of this time of subsidence (called the Champlain epoch) that the lower Hudson and St. Lawrence Valleys were submerged and the seacoast was transferred to more nearly its present position. But the land being even lower than now, the lowlands of Long Island and in the vicinity of New York City were under water and a narrow arm of the sea extended through the Hudson and Champlain Valleys to join a broad arm of the sea which reached up the St. Lawrence Valley and probably also into the Ontario Basin. This so-called Champlain Sea existed at the time of the Nipissing stage of the Great Lakes described beyond (Fig. 309). Champlain Sea beaches, containing marine shells and the bones of walruses and whales, have been found at altitudes of about 400 feet near the southern end of Lake Champlain, 550 feet at its northern end, and 600 feet in the general vicinity of Montreal. The deposits of this age are about 50 feet above sea level near New York City, and at Albany a little over 300 feet. The altitudes of these so-called raised beaches show how much lower the land was during the time of greatest submergence, and that the subsidence was most toward the north. That this greatest submergence occurred after the close of the Ice Age in this region is proved by the fact that the now raised beaches and marine deposits rest upon the latest glacial drift.

The most recent movement of the earth's crust in the New York-New England region was the very gradual elevation which expelled the Champlain Sea and left the land at its present height. The altitudes

of the raised Champlain beaches show that the greatest uplift was on the north. Up-tilting of various post-Glacial (Recent) lake deposits, at the rate of several feet per mile northward, prove the same thing.

Interior Lowland. The great Interior Lowland Province, in the midst of the continent (Fig. 18), has been above sea level and subjected to erosion for a long time—the part from eastern Oklahoma and Wisconsin to New York since the close of the Paleozoic, and the western border and northwestern parts since the close of the Mesozoic era. A general, though moderate, uplift of the region took place in Early Cenozoic time. By the Late Tertiary the region was worn down to a condition varying from old age to a peneplain. This old, low-lying surface was rejuvenated by a general uplift ranging from a few hundred feet to a thousand feet. The modern stream-dissected, hilly surface, with maximum valley depths of a few hundred feet, has developed on the rejuvenated surface. Throughout much of the Interior Lowland, the Pleistocene ice-sheets interrupted the normal work of erosion and filled many valleys with glacial drift. Many streams have since cleared out such valleys or cut through the drift mantle in new places.

Ozark-Ouachita Highlands. The so-called Interior Highland region of Missouri, Arkansas, and Oklahoma has been a land area since Late Paleozoic time. A general upward movement, involving several cycles (or partial cycles) of erosion and base-levelling, occurred during Mesozoic and Tertiary times. The peneplaned region was uplifted 1000 to 3000 feet in Late Tertiary time since which the highly stream-dissected surface of the present time has developed to a condition of maturity. Because of the folded structure of the strata, east-west ridges and valleys have been produced in the Ouachita Mountains, but, in the nearly horizontal strata of the Ozark Plateau, a very irregular ridge and valley pattern has resulted.

Canadian Shield. This vast area, comprising about one-fourth of North America (Fig. 18), has been subjected to erosion since middle Paleozoic time. Most of this time it was probably not high above sea level. In the Late Tertiary the low-lying Canadian Shield seems to have been notably elevated and stream-dissected. Then the great Pleistocene glaciers covered it. Late in the Pleistocene the region subsided to a level lower than that of today, submerging the Hudson Bay and much of the Arctic Islands regions. There is very strong evidence from elevated beaches, etc., especially in the southeast, that, in the present (Recent) epoch, there has been a very considerable, though unequal, re-elevation.

Western North America. *Great Plains.* This vast area, stretching from western Texas far northward into western Canada (Fig. 18), now rises from an altitude of about 1000 feet along its eastern margin to 4000 to 6000 feet along its western margin at the base of the Rocky Mountains. During most of Tertiary time the region was more nearly level, and, especially in the United States and southern Canada, it was the scene of widespread deposition of continental sediments. These sediments were carried out of the mountains and deposited in the form of flood-plain and alluvial-fan materials by the numerous graded and overloaded streams. Sediments of each Cenozoic epoch are represented, but the deposition varied a great deal both in time and place, and locally there was some erosion. The net result of these processes was the development of a plain of aggradation, with a smooth, nearly featureless surface, by Late Tertiary time. Since then the Great Plains region has been differentially uplifted to its present height and with its eastward down-tilt. Wide areas (e.g. northwestern Texas) are still remarkably smooth and little affected by erosion, while other regions of soft sediments, high above sea level, have been more or less deeply dissected, often into so-called "Badlands" (e.g. in southwestern South Dakota).

Pleistocene glacial deposition has often caused modifications of the topography in the northern part of the Great Plains.

The Black Hills of South Dakota stand out so boldly above the Great Plains because the core of a locally formed Late Cretaceous domal anticline, laid bare by erosion, there consists of very resistant pre-Paleozoic igneous and metamorphic rocks.

Rocky Mountains. Only a few of the more important features of the rather complex Cenozoic history of the Rocky Mountain region will be mentioned. The extensive folding, faulting, and vulcanism, which marked Late Cretaceous and Early Eocene times (Rocky Mountain Revolution), left the region topographically high and generally varied. Conditions were thus favorable for rapid erosion of the highlands and deposition of resulting sediments in intermontane basins during Eocene and Oligocene times. As indicated by the nature of the sediments (already described), all sorts of continental materials were laid down, such as lake, flood-plain, alluvial-fan, and volcanic fragmental deposits. Particular mention may be made of the thick and extensive lake beds of Eocene age in southern Wyoming and northern Utah. Marine deposition was entirely lacking. The distribution of the various

formations (Eocene and Oligocene) shows that the principal basins of deposition varied in time and place.

By Miocene time the general relief of the Rocky Mountain region was low because the highlands had been worn down and the basins largely filled with sediment.

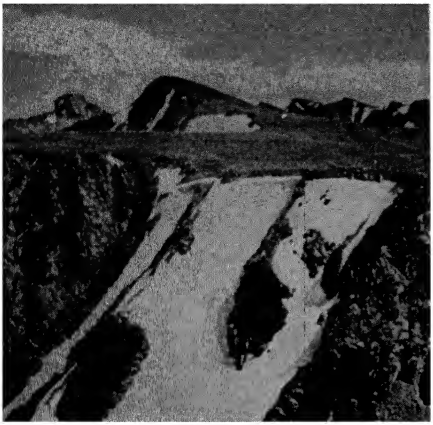


FIG. 252. Remnant of a gently rolling (old age) surface 12,000 feet above sea level in the Rocky Mountains. In Middle Tertiary time it covered a wide region thousands of feet below its present level, and the peaks in the background of the picture were then monadnocks. Flattop Mountain, Rocky Mountain National Park, Colorado. (After W. T. Lee, U. S. Geological Survey.)

In later Tertiary and Quaternary times the general region was greatly rejuvenated by broad uplifts or upwarps, accompanied by very little folding, but with some notable faulting as along the eastern base of the Colorado Front Range, and the western base of the Wasatch Mountains in northern Utah. This uplift reached its climax in the Quaternary, but it was not continuous or uniform as proved by remnants of two or more base-levelled surfaces at widely different altitudes. One of these surfaces, called the Flattop peneplain, is remarkably well preserved at an altitude of about 12,000 feet in Rocky Mountain National Park (Fig. 252). Several erosional stages in the Cenozoic history

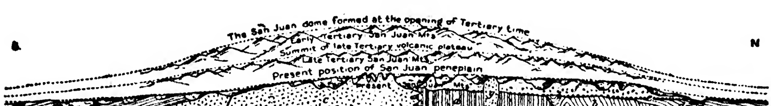


FIG. 253. Diagrammatic cross section showing the physiographic evolution of the San Juan region since the beginning of Tertiary time. *a,* pre-Cambrian schist and gneiss; *b,* Algonkian quartzites; *c,* pre-Cambrian granitic intrusion; *d,* Paleozoic and Mesozoic rocks; *e,* Ridgway till and Telluride conglomerate; *f,* middle and late Tertiary volcanics; *g,* Tertiary intrusives. (After Atwood and Mather, U. S. Geological Survey, Prof. Paper 166.)

of the San Juan region of southwestern Colorado are well shown by Figure 253.

The later Cenozoic rejuvenation of the Rocky Mountains resulted in removal of much Tertiary material, and the bringing into strong relief of the older, harder rocks, by the revived streams, some of which became locally superimposed. Thus the Big Horn, Wind River, Uinta, Medicine Bow, Laramie, Colorado Front, and Sangre de Cristo Ranges, consist of anticlinal cores of hard pre-Paleozoic granites, schists, etc. In other cases, such as the San Juan Mountains of Colorado and most of the mountains of Yellowstone National Park, much of the high, rugged relief is a result of vigorous erosion of Tertiary volcanic rocks. The rugged mountainous region of Glacier National Park consists of a great overthrust block of deeply dissected, relatively hard Proterozoic strata. In northern Utah, the Wasatch Range is an uplifted Cenozoic fault-block.

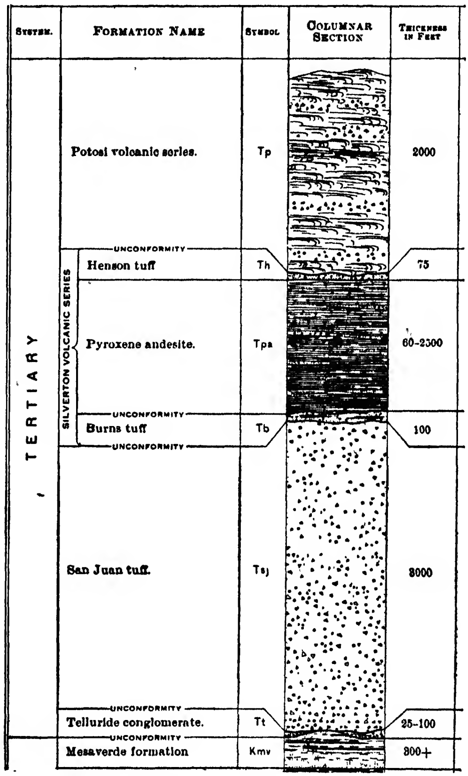


FIG. 254. A columnar section showing volcanic rocks of Tertiary age piled up to a thickness of more than 6000 feet in the Ouray region of southwestern Colorado. The conglomerate near the base is an Eocene glacial deposit. (From U. S. Geological Survey, Ouray folio.)

Vigorous and often long-continued volcanic activity took place throughout much of Tertiary time in various parts of the Rocky Mountains. Particular mention may be made of the tremendous accumulations of volcanic rocks (e.g. San Juan formation) in southwestern Colorado (Fig. 254), and the volcanic plateau and mountains of Yellowstone Park. Small bodies of intrusive rocks were also emplaced here and there.

Pleistocene glaciers in the higher mountains produced many local effects of erosion and deposition.

Colorado Plateau. Eocene continental sediments were laid down extensively over much of the Colorado Plateau region, especially its northern half. Then followed a long interval of erosion interrupted by some broad, gentle folds or upwarps in Miocene time (Fig. 255). By Late Tertiary time the whole region was a low-lying peneplain. More or less extensive lava-flows spread over this peneplain and various volcanic peaks were built up, as for example in the large volcanic district in north-central Arizona. Tertiary laccolithic intrusions occurred in southeastern Utah.

Before the close of the Tertiary there was a moderate general uplift (hundreds of feet only), with some north-south faulting. This re-

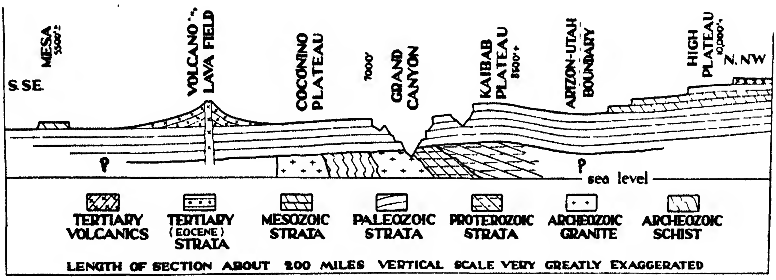


FIG. 255. A highly generalized structure section through the Colorado Plateau showing its principal topographic and geologic features. Note the general southward down-tilt; the Kaibab Plateau upwarp; the remnants of once more widespread Mesozoic and Cenozoic strata, with their steplike topography, at the upper right; the deep-cut Grand Canyon; and the Late Cenozoic volcano.

newed the erosion which produced broad, shallow valleys and a steplike topography, the latter because escarpments were developed along outcrops of certain resistant formations.

The present cycle of erosion began in the Early Quaternary. It was introduced by a profound general uplift of the whole Colorado Plateau region, accompanied by a general northeasterly up-tilt. In the south the plateau was brought to an altitude of about 5000 feet, and in the north to more than 10,000 feet. The uplift caused a vigorous revival of stream erosion, particularly by the great Colorado River which has ever since been busily engaged in carving out the Grand Canyon of Arizona. There has also been some Quaternary volcanic activity as shown by the young cinder cones near Flagstaff, Arizona.

The Grand Canyon is 200 miles long, about a mile deep, and 7 to 15 miles wide. It is still being widened and deepened because the swift,

active Colorado River at the bottom of the canyon is far from graded. The maze of side canyons has been produced by erosive action of tributaries to the main stream. The numerous buttes and mesas, in many places of mountainous size, rising within the canyon are erosional remnants which have not been reduced by erosion as fast as the rest of the rocks. The river has cut through about 5000 feet of nearly horizontal Paleozoic strata, and 1000 feet into the underlying pre-Paleozoic rocks. Outcropping edges of the more resistant Paleozoic formations are in the form of great and small cliffs, while intervening weaker beds are in the form of slopes.

Basin and Range Province. This large physical province (Fig. 18) in the southwestern United States is characterized by many roughly parallel ranges separated by alluvial basins (bolsons). Altitudes vary from 276 feet below sea-level in Death Valley, California, to over 13,000 feet in the Inyo-White Mountains of eastern California.

Most of the region was more or less strongly folded into mountains at the time of the Late Jurassic Sierra Nevada Revolution. During the Cretaceous period and most of the Tertiary, profound erosion reduced the whole region to low relief (old age).

In Late Tertiary time volcanic rocks (mainly lava-flows) covered many large and small parts of the old-age surface.

Beginning in the Late Tertiary, and continuing through the Quaternary, diastrophism (chiefly faulting) has been very active, resulting in the development of the many fault-block mountains and intervening fault-trough valleys, an excellent example of the latter being Death Valley. Particular mention may be made of the great Sierra Nevada fault scarp (modified by erosion) on the western side of the province (Fig. 270), and the Wasatch scarp on the eastern side. In many places the once horizontal lava-flows may now be seen on the backs of block mountains (Fig. 257).

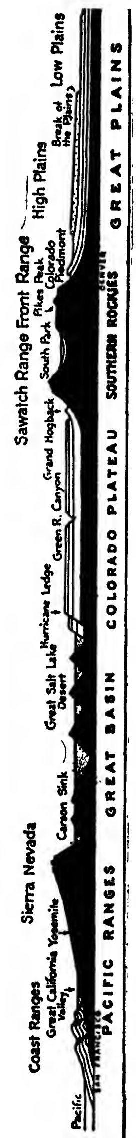


FIG. 256. A diagrammatic structure section across the western United States. The relations of various physiographic provinces are clearly shown. (Drawn by A. K. Lobeck.)

The processes of faulting have varied a good deal in time and place

throughout the province. For this reason many fault scarps are much more modified by erosion than others. Some high scarps are remarkably steep and comparatively little eroded (Fig. 258). In not a few cases fault scarps have recently formed across alluvial cones (Fig. 259). Noticeable dislocations have occurred along some of the faults during the last fifty years.

While the rising mountains have been eroded, the resulting debris has largely been carried into the intermontane basins, most of which

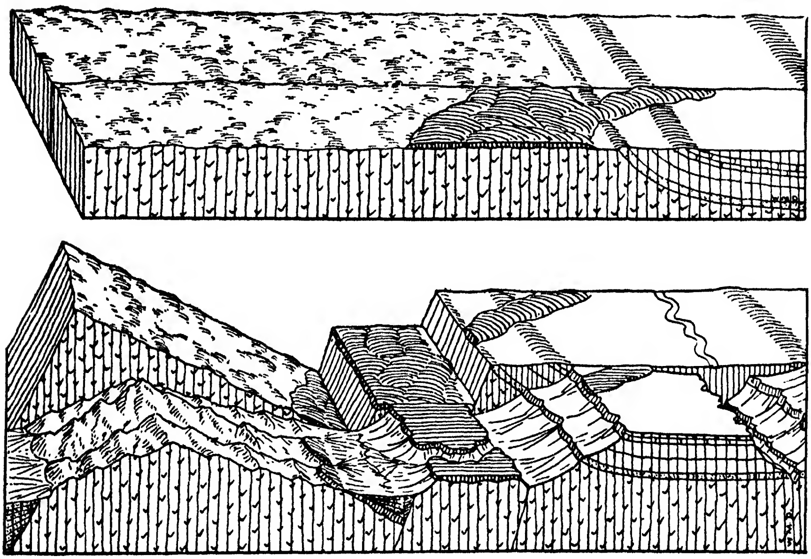


FIG. 257. Block diagrams illustrating typical stages in the later Cenozoic history of the Basin and Range Province. Upper diagram: back part shows the Late Tertiary peneplain, and front part the same partly covered with lava-flows. Lower diagram: back part shows the region after block faulting as it would appear if unaffected by erosion, and front part the actual present-day condition. The particular region here sketched includes the Peacock Range of western Arizona. (Drawn by W. M. Davis.)

have no outlets to the sea. Thus the basins have been aggraded, often to depths of hundreds of feet. Viewed broadly most of the Basin and Range Province is in an early mature stage of the desert cycle of erosion.

Some volcanic action has continued through Quaternary time almost to the present day, as in Owen's Valley and the Mohave Desert, California, where remarkably fresh lava-flows have very recently spread over desert sands, and cinder cones are almost untouched by erosion (Figs. 229, 230).

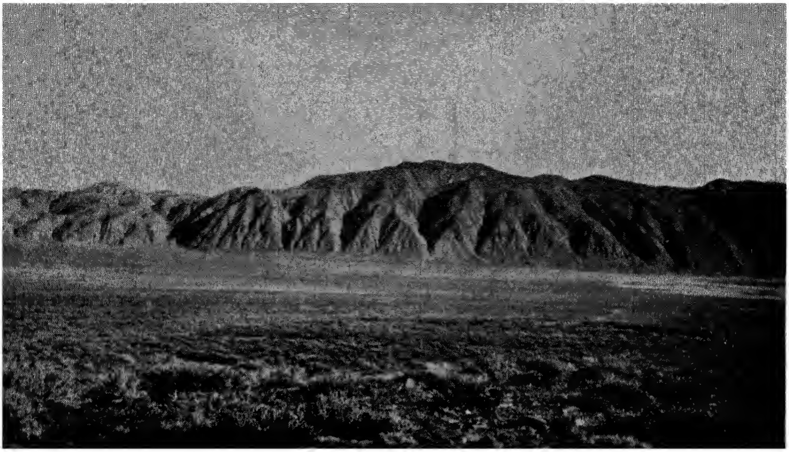


FIG. 258. Great fault-facets of Late Quaternary age on the side of Deep Spring Valley, California. The range rises 3000 feet above the valley floor. The slightly eroded triangular fault-facets are hundreds of feet high. (Photo by R. H. Mansfield.)

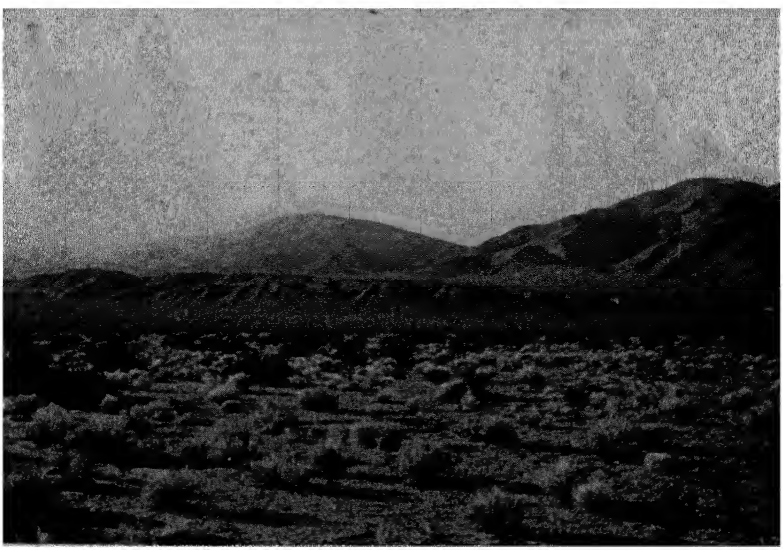


FIG. 259. A fault scarp produced by recent dislocation of a large alluvial cone. Near Goler in the Mohave Desert, California.

During Late Quaternary time the Basin and Range Province had a moister climate than at present, because lakes were much more numerous and larger than now (Fig. 260). One of the largest of these was *Lake Bonneville,* which represented a greatly enlarged stage of the Great Salt Lake. Lake Bonneville was of fresh water; covered 19,000 square miles; and had a maximum depth of 1000 feet. Its remnant, the

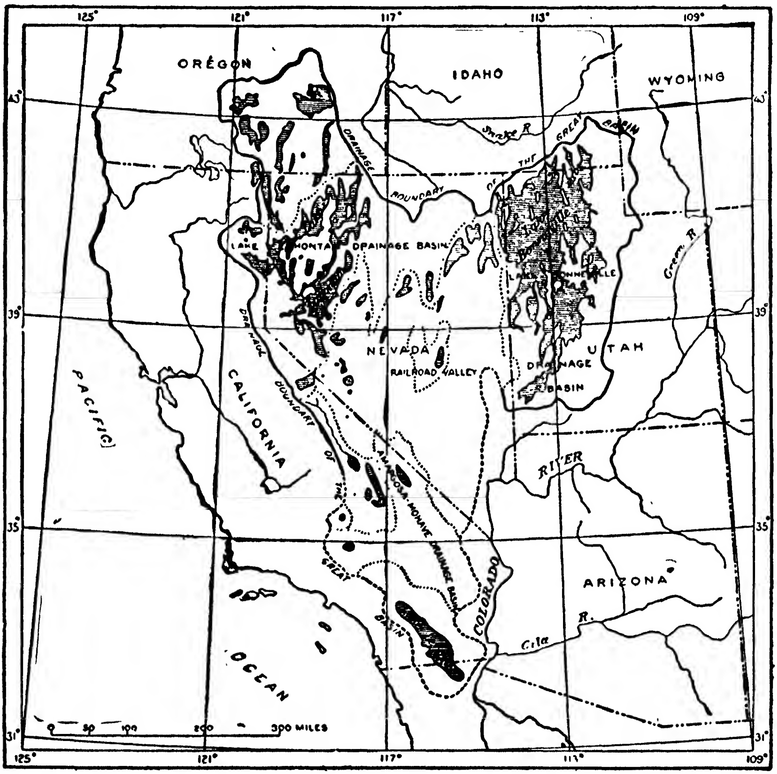


FIG. 260. Map showing the extinct Quaternary lakes of part of the Basin and Range Province. (After U. S. Geological Survey.)

present heavy brine of the Great Salt Lake, covers about 2000 square miles and has a maximum depth of only about 50 feet. The outlet of Lake Bonneville was northward into Snake River. The former existence of this great body of water is positively proved by the perfectly preserved beaches, wave-cut terraces, deltas, etc. Another very large body of water, called *Lake Lahontan,* occupied some thousands of square miles of western Nevada, but it had no outlet. Since the lowering of

the water levels in these basins, crustal disturbances have caused a tilting of the old shore lines some hundreds of feet (Figs. 260, 261).

Columbia Plateau. The building up of the vast lava region known as the Columbia Plateau, covering 125,000 square miles of the northwestern United States between the Cascade and Rocky Mountains, took place during Cenozoic time. It is one of the few greatest lava fields of the world. Fissure eruptions seem to have produced most of the lava-flows which commonly spread far from their sources, and piled up

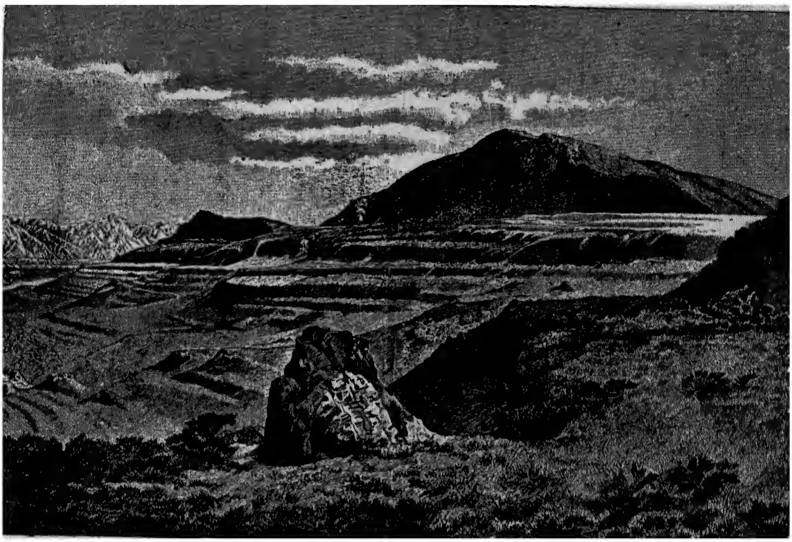


FIG. 261. Lake Bonneville shore terraces on the Oquirrh Range west of Salt Lake City, Utah. Successively lower terraces were formed by wave action during the lowering of the lake. (After G. K. Gilbert, U. S. Geological Survey.)

to thicknesses as great as 5000 feet or more. The vulcanism continued with more or less vigor through Tertiary time, but it was most pronounced and widespread in the Miocene epoch. It gradually diminished during the present (Quaternary) period, some of the most interesting, recent volcanic rocks being in Craters of the Moon National Monument in Idaho.

The evidence from some mountains not buried under the lava (e.g. Blue Mountains, Oregon) and from canyons where buried mountains have been exposed by erosion (e.g. Seven Devils Canyon of Snake River) shows that the pre-lava topography was that of late maturity or early old age of the normal cycle of erosion.

"For thousands of square miles the surface (of the plateau) is a lava plain which meets the boundary mountains as a lake or sea meets a rugged and deeply indented coast. . . . The rivers which drain the plateau—the Snake, the Columbia, and their tributaries—have deeply trenched it, yet their canyons, which reach the depth of several thousand feet, have not been worn to the base of the lava except near the margin and where they cut the summits of mountains drowned beneath the flood. Here and there the plateau has been deformed. . . . The plateau has

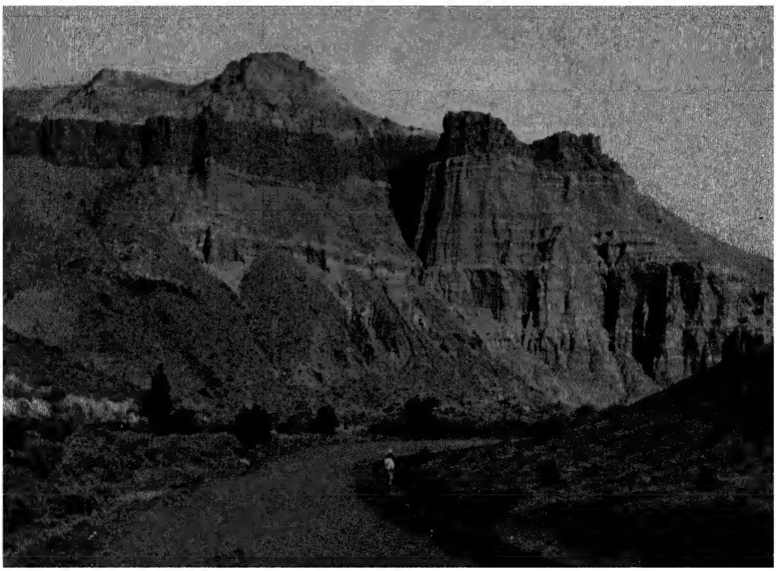


FIG. 262. An exposure of the John Day formation of Oligocene-Miocene age 15 miles north of Dayville, Oregon. The nearly horizontal beds of buff and green tuffs contain an interbedded sheet of red rhyolitic lava (darker layer) in its upper part. (Photo by R. W. Chaney.)

been built like that of Iceland, of innumerable overlapping sheets of lava (Fig. 232). . . . The average thickness of flows seems to be about seventy-five feet.

"The plateau was long in building. Between the layers are found in places old soil beds and forest grounds and the sediments of lakes. . . . So ancient are the latest floods in the Columbia Basin that they have weathered to a residual yellow clay from thirty to sixty feet in depth and marvelously rich in the mineral substances on which plants feed. In the Snake River Valley the latest lavas are much younger.

Their surfaces are so fresh and undecayed that here the effusive eruptions may have continued to within the period of human history." [1]

It should not be understood that all the rocks are lavas. In various places and at different times, fragmental materials accumulated, often to depths of hundreds of feet. A good case in point is the John Day formation of Oregon (Fig. 262). During and after the main eruptions there was some gentle folding (Fig. 232), faulting, and general warping

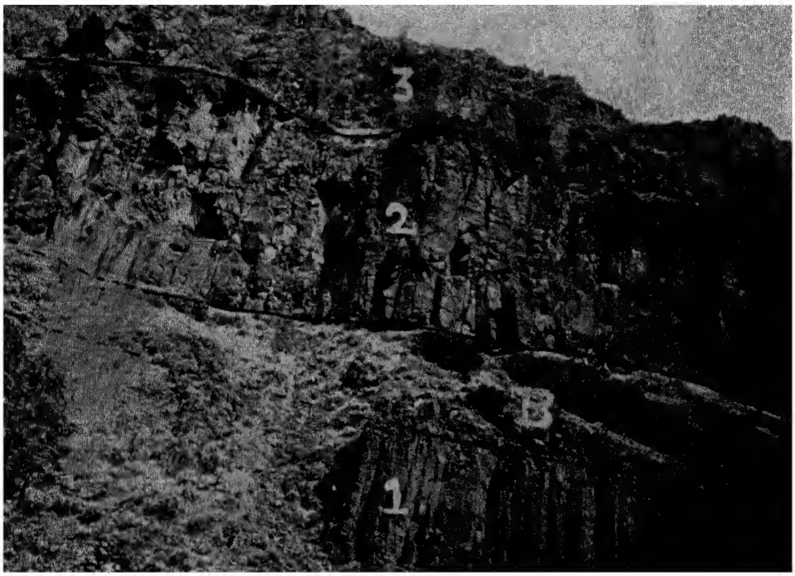


FIG. 263. Three sheets of tilted columnar lava, 1, 2, 3. Numbers 1 and 2 are separated by a bed of volcanic breccia (*B*). The view shows a detail of the volcanic rocks of the Columbia Plateau. Near Dayville, Oregon.

of the region. Extensive *Lake Payette* came into existence because of such deformation in the midst of Tertiary time in eastern Oregon-western Idaho. The lake beds are rich in fossil plants.

Cascade Mountains. The Cascade Mountain region, extending from the Lassen Peak district in northern California through Oregon and Washington (Fig. 18), was more or less folded and elevated toward the close of Jurassic time. Considerable parts of the region were submerged during much of Cretaceous time. Re-elevation of the whole region was followed by much erosion during earlier Tertiary time. Great

[1] W. H. Norton: *Elements of Geology,* pp. 400-401.

FIG. 264. A great volcanic cone of late Cenozoic age rising 8,000 to 10,000 feet above the surrounding country. Mount Shasta, California, as seen from the east. (Photo by J. S. Diller, U. S. Geological Survey.)

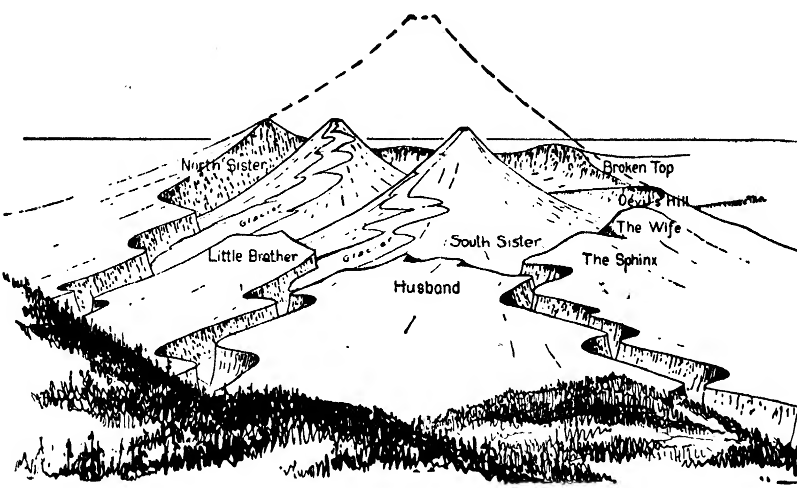


FIG. 265. A sketch showing the former cone of Mt. Multnomah (dotted lines); various parts of the crater rim left after the destruction of the cone; and the two cones (Middle and South Sisters) since built up in the crater. (After E. T. Hodge, University of Oregon Press.)

volcanic activity, mainly in the form of lava outpourings, occurred in the later Tertiary. These volcanics piled up to such a great extent as almost completely to bury the pre-Tertiary rocks in the middle and southern parts of the Cascade region. By latest Tertiary or Early Quaternary time most of the region, particularly in northern Washington, was in an old age or peneplain stage of erosion.

During the Quaternary there has been a great rejuvenation of the Cascade region, accompanied by warping and gentle folding, to form a plateau 4000 to 8000 feet above sea level. That portion of the range which is cut through by the Columbia River was bowed up several thousand feet in the form of a broad anticline or upwarp, 40 miles wide, with its axis parallel to that of the mountains, and the river maintained its course, as an antecedent river, during the uplift.

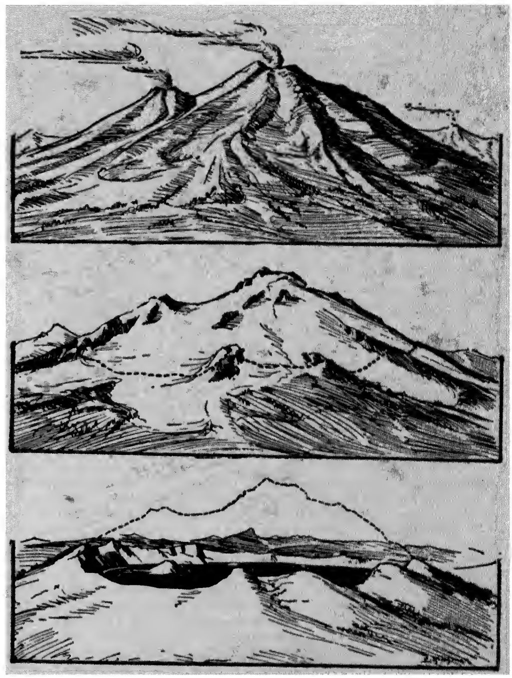


FIG. 266. Sketches illustrating the later history of Mt. Mazama, Oregon. Upper: the full-grown active volcano in Late Pleistocene time. Middle: the cone draped with glaciers during the Late Pleistocene. Lower: the mountain as it now appears after destruction of the cone and partial filling of the resulting great crater pit with water to form Crater Lake. (After W. W. Atwood, Jr.)

During and since the rejuvenation, the plateau has been deeply dissected by streams aided somewhat by glaciers. In the meantime numerous large volcanoes were active from one end of the range to the other, building up a string of cones above the general level of the plateau surface. Among these cones are Lassen Peak, Mt. Shasta, Mt. Pitt, Mt. Hood, Mt. Rainier, and Mt. Baker. Many of the larger cones supported glaciers during the Pleistocene period, and some of them, particularly Mt. Rainier, still do.

A once magnificent cone of Quaternary age, known as Mt. Multnomah, was the ancestor of the Three Sisters in Oregon (Fig. 265). It was destroyed by either explosion or subsidence, leaving a great crater pit. North Sister forms part of the crater rim, and Middle and South Sisters are cones which have been built up by volcanic action within the crater bowl.

Crater Lake, Oregon, 2000 feet deep and nearly 6200 feet above sea level, partly fills a crater pit (or caldera) 6 miles in diameter (Fig. 266). The caldera probably resulted from violent explosive activity followed by collapse of the upper portion of a once great volcanic cone known as Mt. Mazama. Glacial deposits have recently been found interbedded with volcanic rocks in the walls of the caldera facing Crater Lake, thus proving that glaciers existed on Mt. Mazama from time to time while it was building up (Fig. 267).

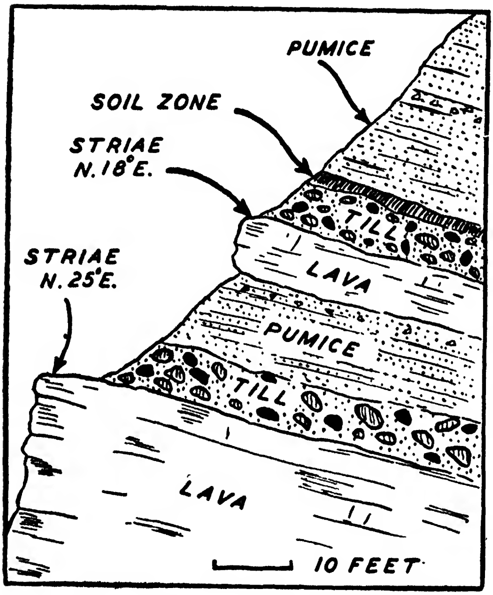


FIG. 267. A detail of the crater wall facing Crater Lake, Oregon, showing glacial deposits interbedded with volcanic rocks, thus proving that at least twice during the building of Mt. Mazama glaciers existed on it. (After W. W. Atwood, Jr.)

A cinder cone and small lava field near Lassen Peak, California, are very young, the latest lava having poured out during the middle of the 19th century (Fig. 268).

Lassen Peak itself erupted explosively many times during the years 1914-1916 (Fig. 269).

Sierra Nevada Mountains. This mountain range extends 400 miles through eastern California and rises to a maximum altitude of 14,496 feet in Mt. Whitney.

As we have already learned, the Sierra Nevada region was highly folded, intruded with granite batholiths, and elevated into lofty mountains toward the close of the Jurassic period. During the Cretaceous

the mountains were worn down to a lowland condition. In the Eocene epoch there was sufficient rejuvenation to cause revived streams to cut

FIG. 268. A recent cinder cone and lava field, several miles long, partly filling a valley in Lassen Volcanic National Park, California. The youngest lava poured out in the middle of the 19th century. (After U. S. Geological Survey.)

canyons 1000 to 2000 feet deep. Most of the famous gold-bearing gravels of the region then accumulated in the stream beds. Volcanic rocks, particularly tuffs, then buried most of the gold-bearing gravels.

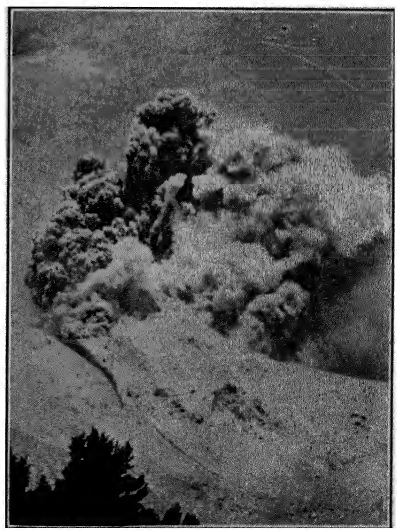


FIG. 269. Lassen Peak in northern California in eruption August 22, 1914. Smoke and volcanic ash rose to a height of 10,000 feet. (From a photograph by R. E. Stinson, Red Bluff, Calif.)

During most of Oligocene and Miocene times, profound erosion reduced the whole Sierra Nevada region to a topographic condition of early old age. Late in the Miocene large parts of the old surface, mainly in the north, were covered with lava flows.

At the end of the Miocene another rejuvenation occurred, this time in the form of a tilted fault-block with a scarp about 3000 feet high along the eastern side, and a much more gradual slope down the western side.

The Pliocene epoch was a time of erosion when the main streams cut canyons 1000 to 1500 feet deep into the western slope.

Early in the Quaternary there began a great renewed uplift of the tilted Sierra Nevada fault-block which continued through the period,

Fig. 270. Part of the great eastern front of the Sierra Nevada, California, facing Owens Valley. This Late Cenozoic fault scarp, modified by erosion, rises 8000 to 10,000 feet above the floor of the valley whose altitude is about 4000 feet. Most of the rock is Late Jurassic granodiorite. (Photo by W. C. Mendenhall, U. S. Geological Survey.)

giving rise to the present-day, lofty range. The streams, which became not only swifter but also larger, deepened the Pliocene canyons so that now many of them are 3000 to 6000 feet deep (e.g. King's River Canyon). Valley glaciers (often very large ones) occupied parts of many of the canyons, and helped to deepen them somewhat and change their shapes, during the Pleistocene Ice Age, as in the case of Yosemite Valley.

Coast Range of the United States. During the Eocene epoch much of western California, Oregon, and Washington were under the sea

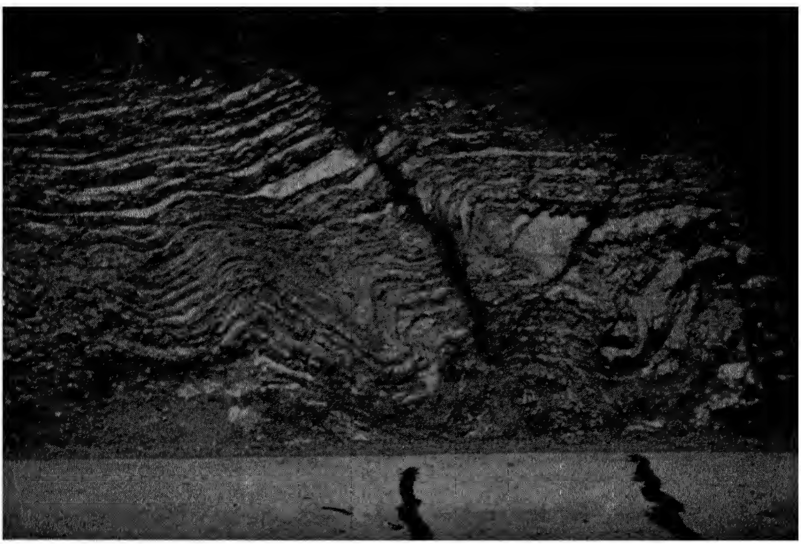


FIG. 271. Locally folded marine strata of Tertiary age in the Coast Range Mountains. Near Las Cruces, California.

most of the time (Fig. 244). Eocene lavas poured out in western Washington and Oregon.

The Oligocene was marked by somewhat greater elevation of the coastal region, causing the sea to be much more restricted (Fig. 245). Non-marine beds, such as the Sespe formation in southern California, piled up in various places.

Submergence of the coastal region, comparable to that of the Eocene, marked earlier Miocene time. In the midst of the Miocene there was pronounced diastrophism, involving local folding and uplift, in the Coast Range region. There were great extrusions of volcanic rocks at this time in southern California. The later Miocene was another important

time of subsidence, particularly in California where the western one-third of the state was submerged. Sediments piled up to great thicknesses in the Miocene seas.

In the Pliocene and earliest Pleistocene the seas were much more restricted than in the Miocene, but in southern California conditions for rapid sedimentation in local basins were so favorable (e.g. Ventura region) that marine strata piled up to the phenomenal thickness of 20,000 feet in such a short time. Non-marine beds of Pliocene and Early Pleistocene ages also accumulated in many places. Considerable

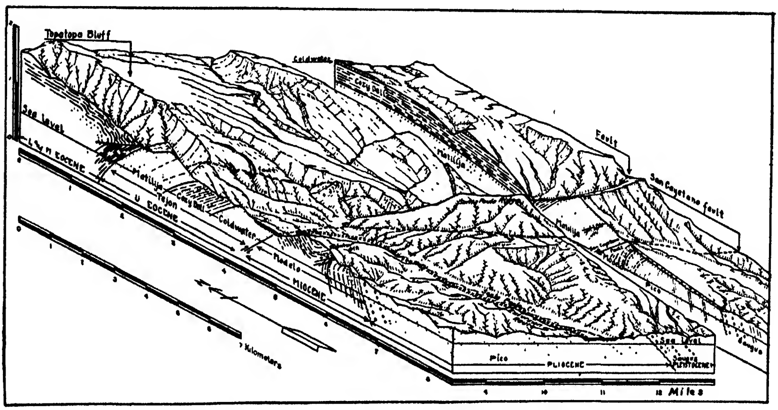


FIG. 272. A block diagram showing topography and structure of the mountains north of Santa Paula in southern California, where upturned and faulted Cenozoic strata are fully 40,000 feet thick. (After P. F. Kerr in Sixteenth International Geological Congress Guidebook 15.)

Pliocene vulcanism occurred in the northern Coast Range region of California.

Well after the opening of the Pleistocene epoch, there was general elevation and great deformation, including much folding and faulting, throughout the Coast Range region. This orogeny, called the *Coast Range Revolution,* has not ended as evidenced by fault movements such as that along part of the great San Andreas fault in 1906. Strata, often 20,000 to 40,000 feet thick, have been more or less profoundly affected by the disturbance. In various places strata as young as Early Pleis-

tocene show strong effects of the diastrophism. The revolution has involved a series of movements varying in intensity, time, and place. Thus Figure 273 shows distinct evidence of two diastrophic episodes, each involving much disturbance of strata during the Pleistocene.

The Great Valley of California, little affected by folding and faulting during Quaternary time, lay between the rising folds of the Coast Range Mountains on the west and the rising Sierra Nevada fault-block on the east.

There are many records of later Quaternary ups and downs in the Coast Range region of the western United States, often amounting to

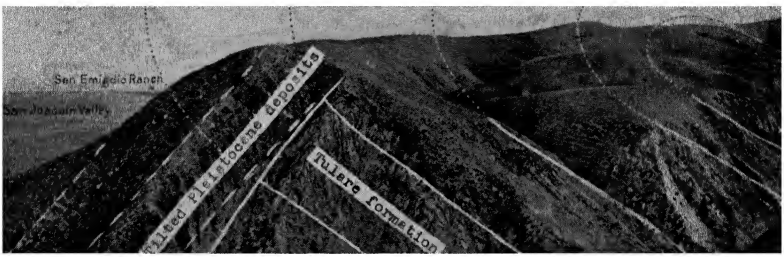


FIG. 273. Steep-dipping Pleistocene beds resting by unconformity upon Late Pliocene-Early Pleistocene (Tulare) beds. The region shows two pronounced diastrophic events within Quaternary time. The Tulare formation was involved in an overturned fold in the Early Pleistocene. Then erosion cut deeply into the fold, and younger Pleistocene alluvial material was laid down on the eroded surface. A second diastrophic episode then affected both of the formations and caused the younger Pleistocene beds, together with the unconformity to be strongly upturned. Southern end of the Great Valley of California. (Photo by H. W. Hoots for the U. S. Geological Survey.)

hundreds of feet, as shown by uplifted marine terraces, and by sunken areas such as San Francisco Bay and Puget Sound.

Mountains of Southwestern California. Some of the principal mountains of southwestern California are the San Gabriel, San Bernardino, San Jacinto, and Peninsular Ranges. They have many points reaching altitudes of 6000 to over 11,000 feet.

During Eocene, Miocene, and Pliocene times the sea spread over the coastal part of southwestern California, including the sites of some of the smaller ranges. Sediments piled up to a great thickness in these marginal seas, particularly in the Los Angeles Basin where Tertiary strata are fully 20,000 feet thick. In Pliocene time the Gulf of California extended farther north than it does today (Fig. 247).

FIG. 274. Strongly inclined marine strata of Early Pleistocene age. West of Santa Paula in southern California. (Photo by U. S. Grant, IV.)

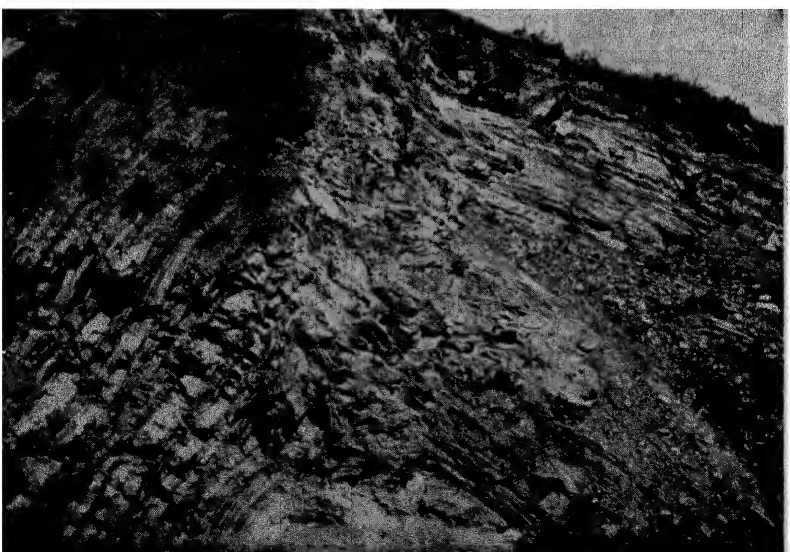


FIG. 275. A small anticline in Lower Miocene sandstone and shale on Avenue 64, Los Angeles, California.

The Tertiary upland region (usually mountainous) facing the marginal seas consisted mostly of hard igneous and metamorphic rocks of pre-Cretaceous age. It was inherited from the mountains formed during the Sierra Nevada Revolution. By Early Pleistocene time the upland region was reduced to an old age or peneplain condition.

Profound diastrophic activity during Quaternary time has resulted in the uplift of large and small bodies of the old hard rocks of the

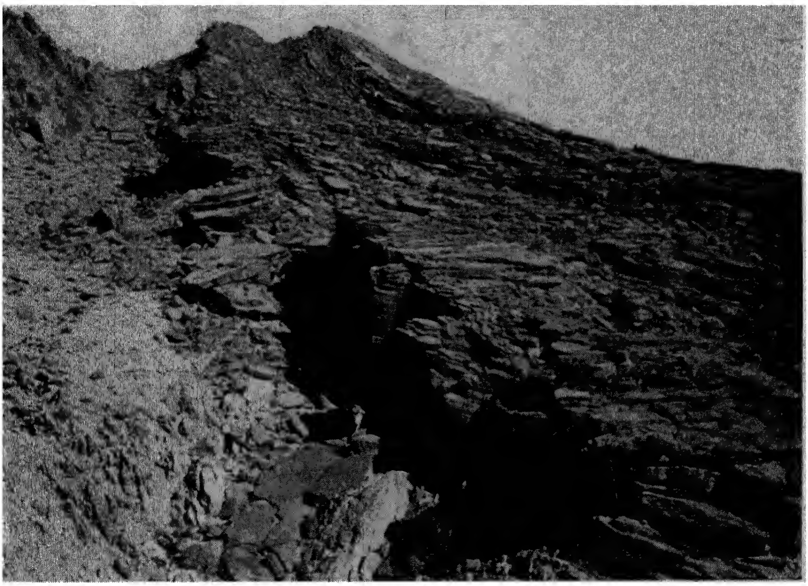


FIG. 276. Upturned marine Pliocene strata faulted against old crystalline rocks on the left. The strata, filled with small oyster shells, were deposited in the Pliocene northward extension of the Gulf of California (Fig. 247). Fish Creek Mountain, western Imperial County, California.

worn-down upland region, in the form of fault blocks, to various heights (Fig. 277). In most cases the mountain blocks rose thousands of feet as so-called horsts between two faults (e.g. San Gabriel Mountains), while in other cases they were upraised as tilted blocks (e.g. Santa Ana Mountains). These mountains have been deeply stream-dissected to a stage of late youth or early maturity. In many places distinct remnants of the former old-age surface are now preserved thousands of feet above sea level. There is some evidence of former small glaciers in the higher mountains.

The Quaternary diastrophism excluded the marginal sea from the coastal belt, and more or less folded the Cenozoic strata (Fig. 282). Much alluvial material, carried out of the mountains by streams, has accumulated over the coastal belt as a surface deposit, often hundreds of feet thick.

The islands off the coast of southern California were also separated from the mainland by the Quaternary diastrophism.

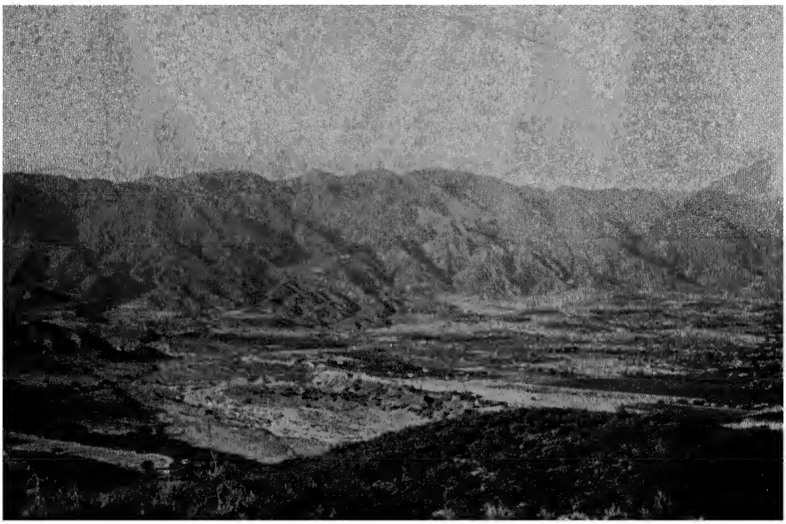


FIG. 277. Part of the San Gabriel Mountains rising 5000 feet above Pasadena, California. These mountains were upraised mainly in earlier Quaternary time. The steep front of the range is a fault scarp much modified by erosion. There are deep canyons back in the mountains. (Photo by J. E. Wolff.)

Uplifted marine terraces are indicators of recent movements along the coast (Fig. 280).

Klamath Mountains. The Klamath Mountains of southwestern Oregon and northwestern California (Fig. 16) had a pre-Cenozoic history much like that of the Sierra Nevada. Their former connection with the latter was buried under great accumulations of Tertiary volcanics.

The mountains formed in Late Jurassic time were reduced to a peneplain by Late Miocene time; uplifted with warping in the Early Pliocene; reduced to low relief again by Late Pliocene time; and generally

rejuvenated by several thousand feet of uplift in the Early Quaternary, thus starting the present cycle of erosion during which the old (plateau) surface has been highly dissected. There were some small Pleistocene glaciers.

Alaska and Western Canada. The later geologic history of this large and complicated Cordilleran region is much less well known than that of the western United States. It involved much mountain-making,

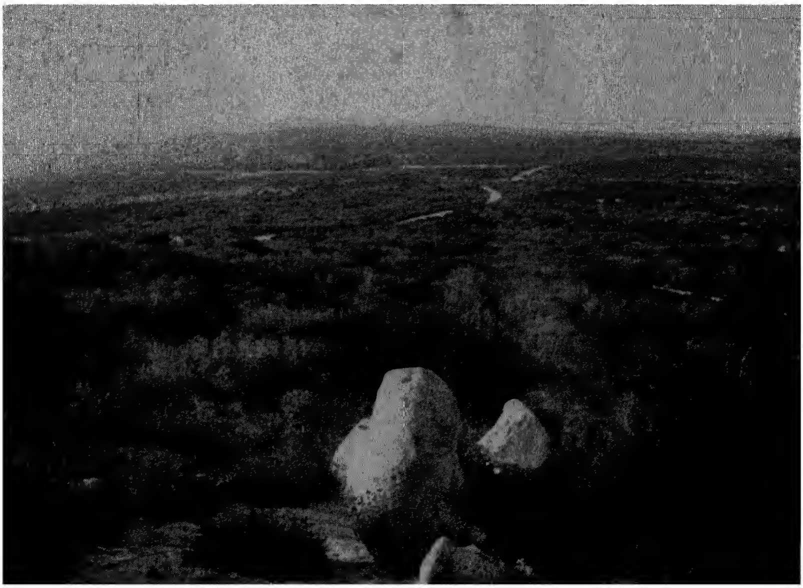


FIG. 278. Part of a peneplain surface of Late Tertiary or Early Quaternary age uplifted to an altitude of 4000 feet and as yet little affected by erosion. Peninsular Range northwest of Jacumba, San Diego County, California.

including folding of strata and batholithic intrusion, in later Mesozoic time, particularly in the Coastal Range and in the Endicott Mountains each of which extend partly through the region; much reduction of the region by erosion during the Tertiary; marine invasions of small parts of the coastal regions in the Tertiary; vulcanism in the Tertiary; widespread Quaternary elevation to about the present altitude; deep dissection of the elevated region by erosion; and continued vulcanism to the present day, especially in the Alaska Peninsula-Aleutian Islands region. Various local changes of level have occurred in later Quaternary time. The numerous glaciers of Alaska, and some in southern British Columbia, are but remnants of the more extensive Pleistocene glaciers.

Western Mexico. The later geologic history of western Mexico, including Lower California, involved mountain-making with folding of strata and batholithic intrusions, in later Mesozoic time; the cutting down of the mountains during the Tertiary; tremendous and widespread volcanic activity during the Tertiary (Fig. 231); an enlarged Gulf of California in the Pliocene (Fig. 247); general Quaternary elevation and erosion; and vulcanism, bringing about present-day conditions.

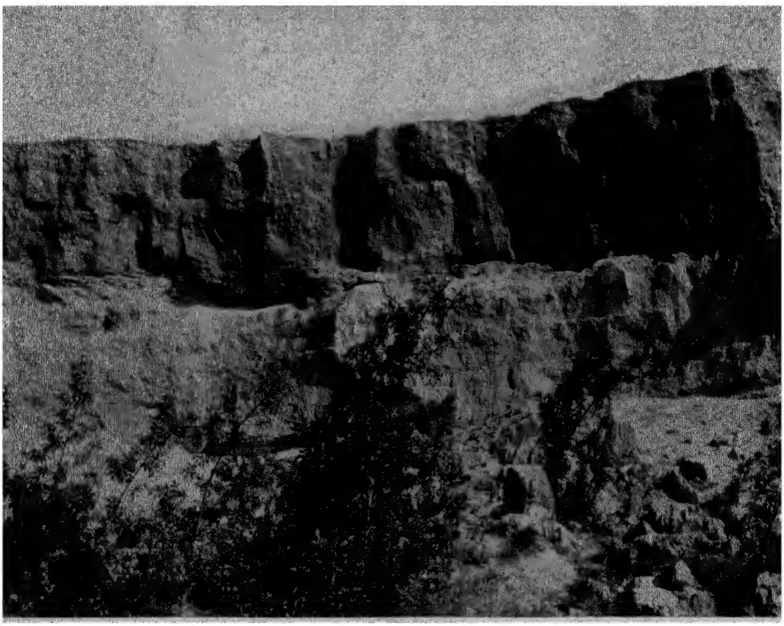


FIG. 279. Marine Pleistocene beds (Palos Verdes), containing warm-water shells, resting by unconformity upon still older marine Pleistocene (San Pedro) beds, containing cool-water shells. San Pedro, California. (Photo by U. S. Grant, IV.)

CLIMATE

During earlier Eocene time the climate of North America was in general notably cooler and drier than that of the present day. This was due mainly to the influence of the great newly formed Rocky Mountains. Glacial deposits of Early Eocene age have been found in Colorado.

From Middle Eocene to Middle Miocene time North America had in general a warm-temperate, moist climate because the high mountains of the West were in such a worn down condition that the warm moisture-

laden winds from the Pacific were free to sweep across the relatively low lands.

During the later Eocene the existence of a subtropical climate well toward the northern boundary of the United States is abundantly proved by the character of the fossil plants and animals.

Over the Great Plains region of the United States the climate, now semiarid, was distinctly moister in the later Eocene and earlier Miocene,

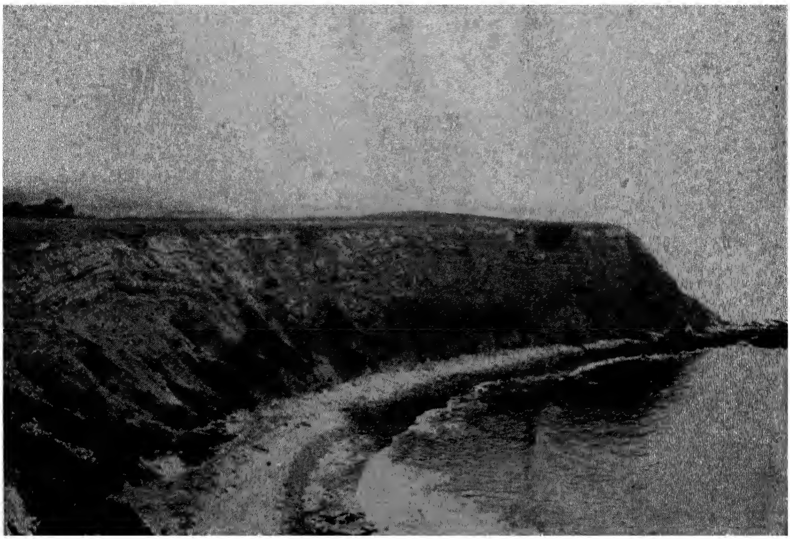


FIG. 280. Two elevated marine terraces on the coast of southern California, near Redondo.

as indicated by the great deposits of lignite which prove the existence of prolific plant life in swamps. Fossil figs, palms, and magnolias in the western interior indicate much warmer and moister climate than now.

Oligocene climate appears to have been somewhat cooler (perhaps warm-temperate) in western North America, and tropical in southeastern North America.

Viewed in a broad way, the climate of the continent gradually became cooler and drier from the Middle Miocene to the Late Pliocene, inclusive, in places reaching Arctic conditions. This was caused by widespread uplifts of the land over the continent, but more especially in the Cordilleran region.

During much of Miocene time the climate of the Pacific Coast was

almost like that of today. On the Atlantic Coast a comparatively cool current, apparently from the north, drove out the warm water forms of the earlier Tertiary. In the western interior region of the United States, subtropical plants gave way to temperate climate plants.

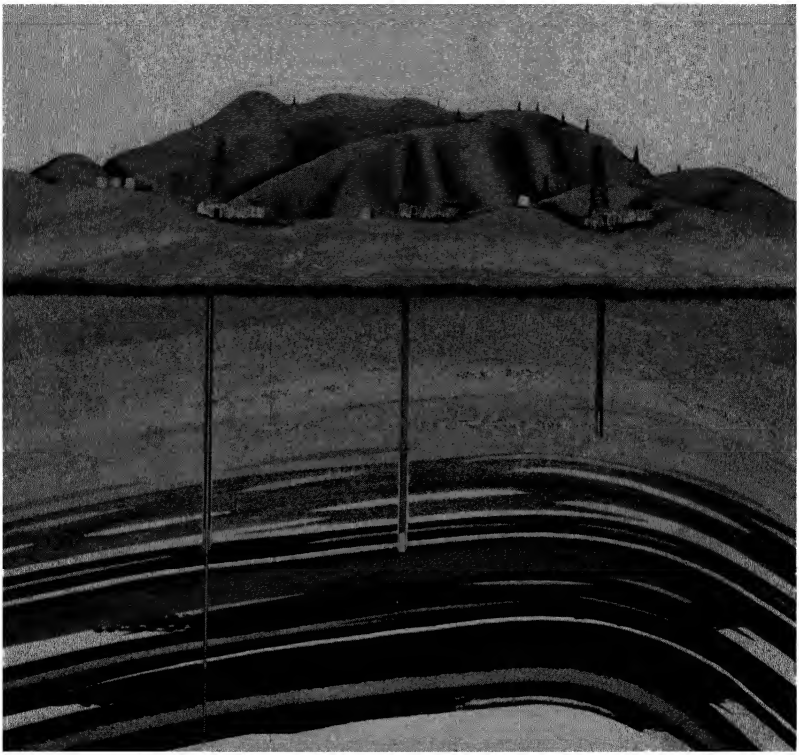


FIG. 281. Photograph of a model of an anticlinal oil field typical of those on the western side of the San Joaquin Valley, California. The structure section in front shows a thickness of thousands of feet of Tertiary strata. Two of the three wells have penetrated "oil sands" (represented in black). Model presented to University of California at Los Angeles by the Standard Oil Company. (Photo by courtesy of Arrow Studio, Los Angeles.)

The Pliocene was in general cooler than the Miocene, in fact, gradually increasing from temperate to sub-Arctic conditions in the waters along the California coast. As judged by the plants, the lands apparently had not become so correspondingly cold during the Pliocene.

The grand climax of Cenozoic cold was reached in the succeeding Glacial epoch of the Quaternary period. During the Ice Age (see

Chapter XXV) there were, however, several great ice invasions with intervening, mild-climate, non-glacial stages as proved by kinds of fossil plants found in interglacial deposits. As a proof of temperature changes in the sea water during the Glacial epoch, mention may be made of a marine deposit with warm-water fossils resting upon another with cool-water fossils in southern California (Fig. 279).

The climate of the present (or Recent) epoch is milder than that of the last great ice invasion, but it is cooler than that of certain interglacial stages. It is possible that we are living in an interglacial stage.

Economic Products

A large production of petroleum and natural gas comes from southern California where it is obtained mostly from Tertiary strata. It seems probable that this petroleum originated from the decomposition of countless myriads of diatoms and other organisms in certain of the

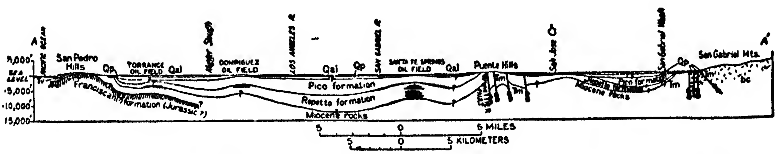


FIG. 282. Structure section across the Los Angeles Basin in southern California showing the location of three anticlinal oil fields. About 15,000 feet of Tertiary strata, capped with Quaternary deposits (*Qp, Qal*), are shown in relation to the underlying pre-Tertiary crystalline rocks. (After H. W. Hoots, International Geological Congress Guidebook 15, 1933.)

shales. Porous sandstones of Miocene and Pliocene ages, lying between impervious shale beds, are the most prolific sources of the oil. As usual in the oil fields of the world, anticlinal structures are by far most common (Fig. 281). Where oil-bearing beds also contain gas under high pressure, the oil may be forced out of a well and high into the air. These are so-called "gushers." Many of the wells are from one to two miles deep.

Large quantities of oil have also been obtained from Tertiary beds in southeastern Texas and southwestern Louisiana where oil-bearing strata are upturned around large masses of salt (so-called "salt domes"). Much oil comes from Tertiary strata in other parts of the world such as southern Russia, Venezuela, Roumania, and the East Indies.

Lignite (or brown coal) underlies thousands of square miles of both the Gulf States and the western interior regions, as well as smaller areas

on the Pacific Coast. There are also important lignite deposits in Europe, particularly in Germany.

Many important gold deposits of California occur in Tertiary river gravels, which are often capped by lava. This so-called placer gold was derived (by erosion) from the gold-bearing veins already described as having formed at the time of the Sierra Nevada Revolution. The famous gold deposits at Cripple Creek, Colorado, and at Tonopah, Ne-

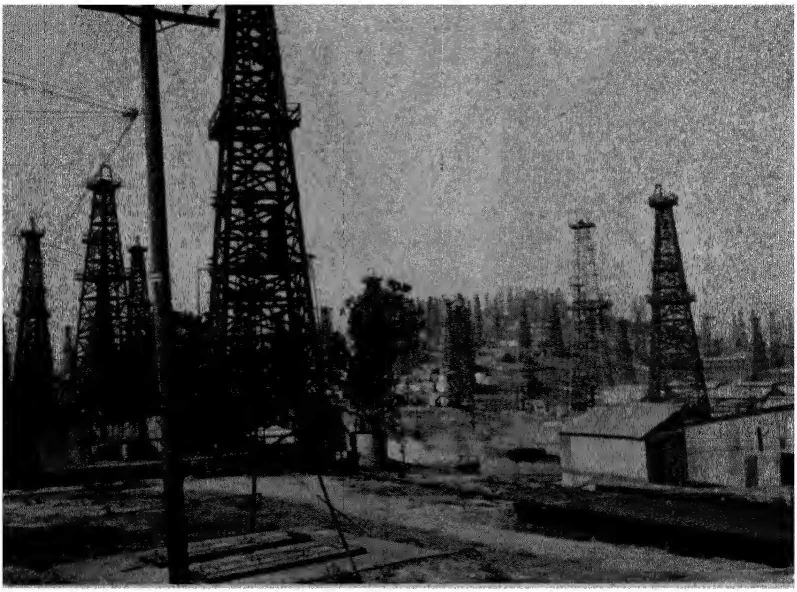


FIG. 283. Oil wells on an anticlinal ridge formed by folding in later Quaternary time. The deeper wells first penetrate Quaternary marine beds, and then thousands of feet of marine Pliocene and Miocene strata which contain several oil-rich horizons. Signal Hill, Long Beach, California.

vada; the copper deposits at Butte, Montana; and other metalliferous deposits occur as veins in, or adjacent to, Tertiary igneous rocks.

Fine pottery clays of Tertiary age occur at various places.

Some Tertiary building stone is quarried on the Pacific Coast.

Tertiary diatomite is mined in various regions, particularly in southern California. It consists of the siliceous tests of single-celled plants (Fig. 237). It is used in the manufacture of polishing powders, heat insulators, filtering material, porous brick, etc.

Valuable phosphate deposits occur in the Tertiary limestones of Florida.

Foreign Cenozoic

Eocene. Just after the emergence of much of Europe at the close of the Mesozoic, there were certain basins of deposition such as lakes, estuaries, etc. Early in the Eocene, however, a great submergence set in, allowing marine waters to spread over a considerable part of western and much of southern Europe. The southeastern British Isles, the

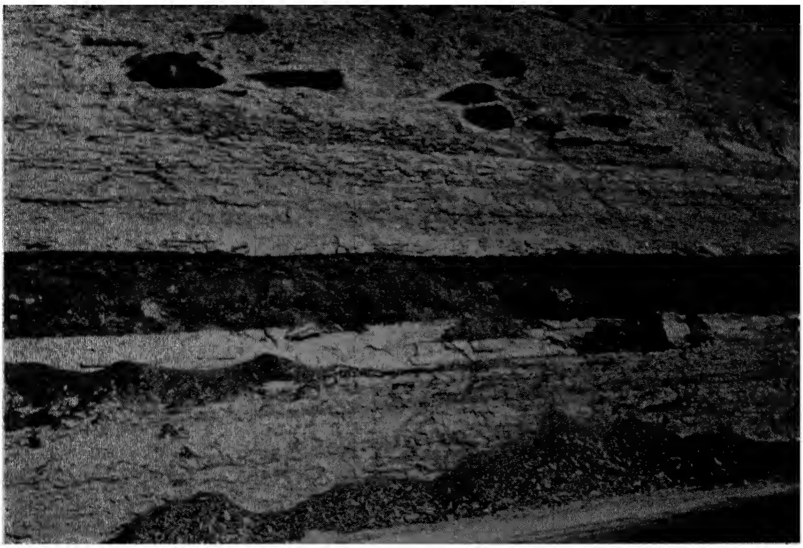


Fig. 284. A bed of lignitic coal nearly two feet thick in Tertiary strata. Near Rock Springs, Wyoming.

northern border of France, Belgium, Holland, the northern border of Germany, the site of the Pyrenees, Italy, all but the axis of the Alps, much of southeastern Europe, and northern Africa were submerged. This greatly expanded mediterranean of Europe also extended eastward across southwestern Asia, except southern Arabia and southern India, to connect with the Indian Ocean through the Bay of Bengal. A narrow sound along the eastern side of the Urals connected this mediterranean with the Arctic. In this vastly expanded interior sea true marine deposition took place, the most characteristic formation being known as nummulitic limestone, so called because it is made up chiefly of shells of a certain genus (Nummulites) of unusually large foraminifers. Perhaps no other formation in the crust of the earth, built up essentially of

the remains of but one genus of organism, is so widespread and thick, its thickness at times reaching several thousand feet. This marine nummulitic limestone now occurs at altitudes of 10,000 feet in the Alps, and fully 20,000 feet in Tibet. Limestone of this age was quarried for the building of Egyptian pyramids.

During Eocene time also the island region along the eastern coast of Asia was largely submerged as well as the eastern coasts of Australia and South America (in Argentina and Brazil). Land seems to have been continuous in the northern hemisphere except for the narrow strait or sound just east of the Ural Mountains.

Toward the close of the Eocene the Pyrenees Mountains were upraised by folding. Moderate orogenic movements took place during later Eocene time in the regions of the Alps, Carpathians, and Himalayas, as well as in some other mountain areas.

Oligocene. The Oligocene is best known in Europe, while in many other parts of the world it has not yet been separated from the Eocene or Miocene. During the Oligocene a shallow sea transgressed over northern Germany. In many places there were lagoons, estuaries, and even basins in which terrestrial deposits were formed. Some beds of gypsum, salt, and brown coal (lignite) were formed. Oligocene strata are especially well developed throughout southern Europe. In Italy, marine deposits of this age have an estimated thickness of 12,000 feet. In southern Europe true marine conditions prevailed, though continental deposition also occurred.

There was much igneous activity during this epoch, particularly in Bohemia, Ireland, Scotland, Iceland, and in the vicinity of Vienna.

During Late Oligocene time severe orogenic movements affected various regions such as the Alps, Carpathians, Balkans, and Himalayas. In some cases (e.g. Alps) great recumbent folds were produced.

Oligocene rocks are also quite certainly present in the Caucasus Mountains, southwestern Asia, and northern Africa, but they have not been much studied in other countries.

Miocene. Viewed in a broad way, the Miocene land and water areas of Europe were much as they had been in the Eocene, all but the northern coast of Germany again becoming dry land. Marine waters occupied parts of the Atlantic borders of France and the Iberian peninsula, while southern Europe was largely submerged as in the Eocene, except for considerable land masses occupying such areas as the interior of Spain and France, portions of the sites of the Alps, Pyrenees, Car-

pathians, Apennines, etc., which had been more or less affected by orogenic movements before the Miocene. A remarkable formation, worthy of special mention, is an extensive conglomerate several thousand feet thick along the northern side of the present Alps. This conglomerate has considerably controlled the topography, for instance in the vicinity of Lucerne.

The vast Eocene mediterranean across southwestern Asia was not continued into the Miocene. Eocene strata, both marine and non-marine, occur in northern Africa and Syria, but not in the Persian region. Though not yet well studied, Miocene strata are well developed in southern Asia, Japan, and northeastern Asia and Australia. In South America the Miocene is extensively shown in Argentina and probably also on the western coast of the continent.

The Caucasus Mountains were also upraised not earlier than in Late Miocene, since Miocene strata are there found about 7000 feet above sea level.

Volcanic activity occurred in many parts of the world during Miocene time.

Pliocene. The Pliocene opened with comparatively little of Europe under marine waters, only a little of southern England, Belgium, the northwestern border of Germany, a little of southern France, and much of Italy having been submerged. Only in Italy are thick marine deposits known where the sediments washed from the newly built Apennines accumulated to a thickness of from 1000 to 3000 feet. Since some of these deposits now lie at altitudes of 2000 to 3000 feet, it is evident that the Apennines were again notably upraised after the deposition of the Pliocene sediments.

Strong orogenic forces affected important parts of Europe and Asia toward the close of Pliocene time. Thus the Alps, Carpathians, Balkans, and Himalayas were again subjected to pressure and re-elevated.

Volcanoes were active in many parts of the world during Pliocene time, especially in the Mediterranean region, East Indies, and around much of the Pacific Ocean.

In southeastern Europe conditions were favorable for much deposition of continental material—lake, river, and terrestrial deposits.

Marine Pliocene extends up the Nile Valley for many miles. As a result of the erosion of the newly upraised Himalayas, a deposit of sandstones, conglomerates, shales, etc., thousands of feet thick, accumulated at the southern base of those mountains during Pliocene time.

In South America Pliocene deposition took place over much of southern Argentina, deposits of this age being upturned on the eastern flank of the southern Andes.

Quaternary. During Late Pliocene and Pleistocene times continued orogeny brought the Alps, Carpathians, and Himalayas to their present heights. In the Alps the great recumbent folds continued to be stretched and pushed northward many miles.

Pleistocene ice sheets covered about 2,000,000 square miles of northern Europe (Fig. 317).

Europe in the Pleistocene stood generally higher than it does today, extending out to about the edge of the present continental shelf. The British Isles were connected and in turn joined the continent across the North Sea and English Channel regions. Europe and Africa were joined by land across the Gibraltar region, and also across the Mediterranean region from Italy to Tunis. Post-Glacial subsidence, followed by partial re-elevation in the north (e.g. Scandinavia), has brought about the conditions of today.

The later Cenozoic history of the Andes Mountains is much like that of the Rocky Mountains. The largely base-leveled region of Late Tertiary time was re-elevated thousands of feet with warping, but with little folding.

In Asia during the Pleistocene "the islands of the Malay Archipelago, Borneo, Java, Sumatra, Celebes, the Philippines, as well as Japan, Formosa, and the Kuriles, were parts of the mainland, though probably not all at the same time. Asia and North America were united where now is Bering Sea, and made a broad highway of intercommunication for northern animals" (W. B. Scott).

The great string of active volcanoes now bordering the Pacific Ocean, as well as those of the Hawaiian Islands, East Indies, Mediterranean, and West Indies, came into existence during Pliocene and Quaternary times.

CHAPTER XXV

PLEISTOCENE GLACIATION

The Fact of the Ice Age

The Pleistocene epoch was ushered in by the spreading of vast ice sheets over much of northern North America and northern Europe. This event ranks as one of the most interesting and remarkable occurrences of geological time. On first thought, the existence of such vast ice sheets seems unbelievable, but this so-called Ice Age occurred so short a time ago that the records of the event are perfectly clear and conclusive. The fact of this great Ice Age was discovered by Louis Agassiz in 1837, and fully announced before the British Scientific Association in 1840. For some years the idea was opposed, especially by advocates of the so-called iceberg theory. Now, however, no important event of earth history is more firmly established and no student of the subject ever questions the fact of the Pleistocene Ice Age.

Some of the proofs for the former presence of the great ice sheets are as follows: (1) Polished and striated rock surfaces which are precisely like those produced by existing glaciers, and which could not possibly have been produced by any other agency; (2) glacial boulders or "erratics," which are often somewhat rounded and scratched, and which have often been transported many miles from their parent rock ledges; (3) true glacial moraines, especially terminal moraines, like that which extends the full length of Long Island and marks the southernmost limit of the ice sheet there; (4) the generally widespread distribution, over most of the glaciated area, of heterogeneous glacial debris (so-called "drift") both unstratified and stratified, which is clearly transported material and typically rests upon the bed-rock by sharp contact. In regions which have not been glaciated, it is quite the rule to find that the underlying fresh rock grades upward through rotten rock into soil.

Ice Extent and Centers of Accumulation

The best known existing ice sheets are those of Greenland and Antarctica, particularly the former, which covers about 500,000 square

miles. This glacier is so large and deep that only an occasional high rocky mountain projects above its surface, and the ice is known to be slowly moving outward in all directions from the interior to the margins of Greenland. Along the margins, where melting is more rapid, some

FIG. 285. Map of North America showing the maximum extent of glaciers during the Pleistocene Ice Age. The locations and general directions of movement of the great ice sheets are indicated, and regions of local mountain glaciers are shown in black. (Modified after U. S. Geological Survey.)

land is exposed, but often the ice flows out into the ocean, where it breaks off to form large icebergs.

The accompanying map (Fig. 285) shows the area of nearly 4,000,000 square miles of North America covered by ice at the time of maximum glaciation, and also the three great centers of accumulation and dis-

persal of the ice. The directions of flow of the ice from these centers have been determined by the study of the directions of a very large number of glacial striæ as well as the direction of transportation of the glacial debris. Greenland was also buried under ice during the Pleistocene epoch much as it is today.

Two striking features regarding the distribution of the ice were (1) the failure of the ice to cover any of Alaska except its high mountain regions, though that country is much farther north than most of the

Fig. 286. A remarkable record of two glaciations hundreds of millions of years apart. Thoroughly consolidated boulder-bearing glacial till of Proterozoic (Huronian) age which has been planed off, striated, and polished by a Pleistocene ice sheet. Near Thessalon, Ontario, Canada. (Photo by A. P. Coleman.)

glaciated area; and (2) the failure of anything like continuous ice sheets over the high plateaus of the western United States, while the great ice sheet spread over much of the low plains area of the upper Mississippi Basin.

From its center of accumulation, the Labradorean ice sheet extended fully 1600 miles southwestward or to about the mouth of the Ohio River. The Keewatin sheet extended from its center southward nearly as far, or into northern Missouri. These two great ice sheets practically merged. "One of the most marvelous features of the ice

dispersion was the great extension of the Keewatin sheet from a low flat center westward and southwestward over what is now a semiarid plain, rising in the direction in which the ice moved, while the mountain glaciers on the west, where now known, pushed eastward but little beyond the foothills" (Chamberlin and Salisbury).

The Cordilleran ice sheet appears to have been mostly made up of both plateau and typical mountain (Alpine) glaciers. Toward the south it extended only a little way over the high mountains of the northwestern United States.

FIG. 287. Glaciated surface of granite high up on the side of a deep canyon. Middle Fork of King's River near Paradise Valley, California.

Newfoundland probably had a local center of glaciation.

South of the ice sheets above described, the higher mountains of the United States, even as far south as southern California, Arizona, and New Mexico, bore numerous glaciers greatly varying in size (Fig. 285). These were always of the typical valley or Alpine types instead of ice sheets. Some of these mountains, such as Shasta, Hood, Rainier, and those of the Glacier National Park in Montana, still have glaciers, the greatest being those on Mount Rainier, where they attain lengths of from 4 to 6 miles. The Pleistocene glaciers were, however, far larger and more numerous in these mountain regions (Fig. 285).

Direction of Movement and Depth of Ice

The fact that glacial ice flows as though it were a viscous substance is well known from studies of present-day glaciers in the Alps, Alaska, and Greenland. A common assumption, either that the land at the center of accumulation must have been thousands of feet higher, or that the ice must have been immensely thick, in order to permit flowage so far out from the center, is not necessary. For instance, if one proceeds to pour viscous tar slowly in one place upon a perfectly smooth (level)

surface, the substance will gradually flow out in all directions, and at no time will the tar at the center of accumulation be very much thicker than at other places. The movement of the ice from each of the great centers was much like this, only in the case of the glacier the piling up of snow and ice was by no means confined to the centers of accumulation.

FIG. 288. A map of Rocky Mountain National Park, Colorado, showing the extent of a great system of former (Pleistocene) glaciers (dotted areas). Only a few very small remnants of these glaciers exist today. Area shown, 19 × 27 miles. Altitude of Longs Peak, 14,255 feet. (Modified after W. T. Lee, U. S. Geological Survey.)

Some of the finest examples of the influence of topography upon the direction of movement of the ice are afforded by New York State on account of its peculiar relief features (Fig. 289). When the last Labradorean ice sheet spread southward as far as northern New York, the Adirondack Mountains stood out as a considerable obstacle in the path of the moving ice, and the tendency was for the current to divide into two portions, one of which passed southwestward up the low, broad St. Lawrence Valley, and the other due southward through the deep, nar-

row Champlain Valley. As the ice kept crowding from the rear, part of the St. Lawrence ice lobe pushed into the Ontario basin. As the Ontario lobe increased in size it sent a branch lobe eastward into the Mohawk Valley. At the same time the Champlain ice lobe found its way into the upper Hudson Valley, and sent a branch lobe westward up the broad, low Mohawk Valley. The two Mohawk lobes, the one

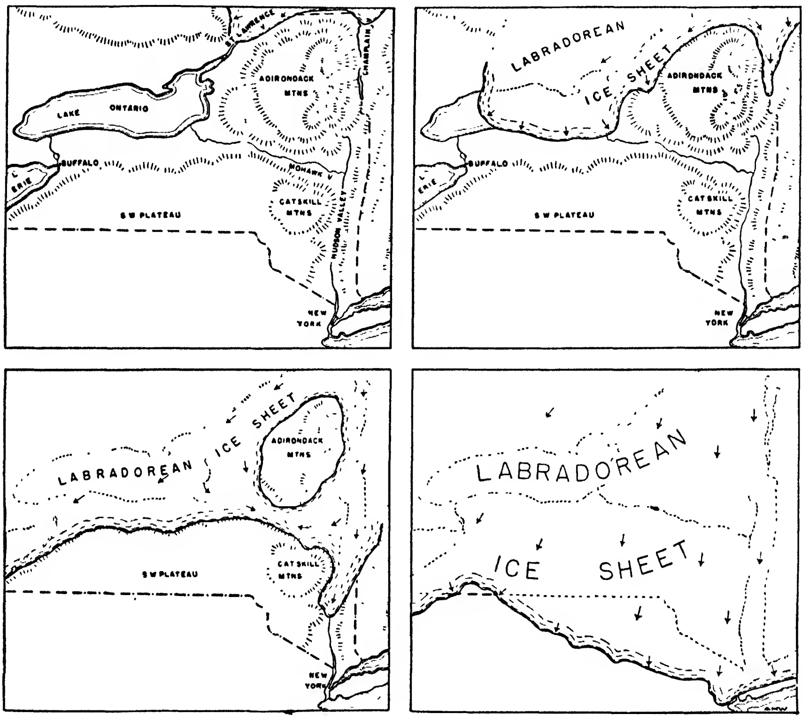


FIG. 289. Maps showing the influence of the topography upon the movement (or flowage) of the Labradorean ice sheet across New York State. Note the strong directive control of the Adirondack highland region. When nearly all of the state was covered, the general movement of at least the upper part of the glacier was southward to southwestward as indicated by the arrows.

from the west and the other from the east, met in the midst of the Mohawk Valley. As the ice sheet continued to push southward, all the lowlands of northern New York were filled; a tongue or lobe was sent down the Hudson Valley; and finally the whole state, except slight portions of the southern border, was buried under the ice. The general direction of flow at this time of maximum glaciation was southward to southwestward, with perhaps some undercurrents determined by the

larger topographic features. Thus we learn that the major relief features of the state very largely determined the direction of ice currents, except at the time of maximum glaciation, when only the undercurrents were controlled. These ideas are abundantly borne out by the distribution of glacial striæ and boulders over the state.

Evidences of glaciation, such as striæ boulders, lakes, etc., occur high up in the Adirondacks, the Catskills, the Green and the White Mountains, and the Berkshire Hills, so that the greatest depth of ice over New York and New England could not have been less than one or two miles. In fact we have every reason to believe that all of the mountains named were completely buried. The reader may wonder how the ice over a mile thick in northern New York could have thinned out to disappearance at or near the southern border of the state, but observations on existing glaciers show that it is quite the habit of extensive ice bodies to thin out very rapidly near the margins, thus producing steep slopes along the ice fronts.

There is little reason to doubt that the vast ice sheet over the upper Mississippi Valley was also thousands of feet thick. The positions of the moraines there clearly prove that the ice front was more or less distinctly lobate.

Successive Ice Invasions

The front of the great ice sheet, like that of ordinary valley glaciers, must have shown many advances and retreats. In the northern Mississippi Valley, however, we have positive proof of several important advances and retreats of the ice which gave rise to true interglacial stages. The strongest evidence is the presence of successive layers of glacial debris, a given layer often having been oxidized, eroded, and covered with vegetation before the next (overlying) layer was deposited (see Fig. 290). In drilling wells through the glacial deposits of Iowa, for example, two distinct layers of vegetation are often encountered at depths of from 100 to 200 feet. Near Toronto, Canada, plants which actually belong much farther south in a warm climate have been found between two layers of glacial debris. Thus we know that some, at least, of the ice retreats produced interglacial stages with warmer climate and were sufficient greatly to reduce the size of the continental ice sheet or possibly to cause its entire disappearance.

By applying the principles just laid down, at least four advances and retreats of the ice, with distinct interglacial intervals, have been recognized in North America as follows:

Period (System)	Epoch (Series)	Age (Stage)	"Epochs" after Kay & Leighton
Quaternary	Recent	Post-Glacial	Eldoran
	Pleistocene	Wisconsin (glacial) (Peorian loess) { Mankato, Cary, Tazewell, Iowan	
		Sangamon (interglacial) Illinoian (glacial)	Centralian
		Yarmouth (interglacial) Kansan (glacial)	Ottumwan
		Aftonian (interglacial) Nebraskan (glacial)	Grandian

The various glacial and interglacial deposits are by no means everywhere always present, first, because, in many places, older deposits were eroded away before younger deposits were laid down, and, second, because the various ice sheets differed considerably in regard to the areas they covered, especially within a few hundred miles of the southern limit of glaciation. Thus in Figure 290 the Centralian deposits are

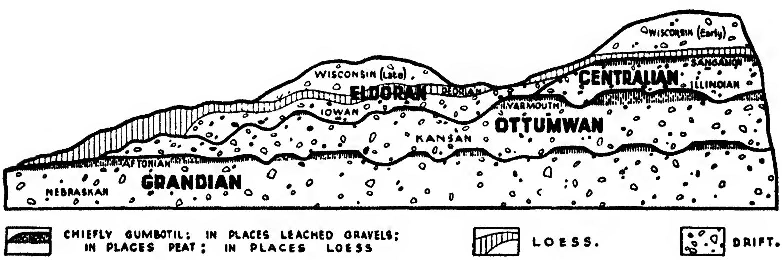


FIG. 290. Diagrammatic structure section showing relationships of the main divisions and subdivisions of the Pleistocene deposits in the Mississippi Valley. (After G. F. Kay.)

seen to be missing between the Eldoran and Ottumwan over a large region.

In New York and New England no very positive evidence has as yet been found to prove truly multiple glaciation, though some phenomena as, for example, certain buried gorges, are difficult to account for except on the basis of more than one advance and retreat of the ice. At any rate, there appears to be no good reason to believe that there were more than two advances and retreats of the ice over this region.

For our purpose in considering only the general movements and effects of the great ice sheets, we may practically disregard the problem

of multiple glaciation, because the final effects would have been essentially the same as a result of a single great glacial advance and retreat.

Recent studies have shown that multiple glaciation also occurred in the mountains of the west (Cordilleran region), beyond the limits of the vast ice sheets, during the Ice Age. Thus, in the Sierra Nevada Mountains of California, valley glaciers came and went three (and possibly four) times, as indicated by several glacial deposits of distinctly different ages. These glacial stages very likely correlate with stages of the great ice sheets.

The Driftless Areas

In southwestern Wisconsin, and extending a little into adjoining states, there is a non-glaciated area of about 10,000 square miles which lies several hundred miles north of the southern limit of the ice sheets (see Fig. 285). This is called the "driftless area," because of the utter absence of glacial debris or any other evidence of glaciation within its boundary. In spite of several ice invasions on all sides, this small area was never ice covered. Residual soils and rotten rock are widespread; there are no lakes; and the streams are mostly graded and without waterfalls or rapids. There are also numerous large outcrops of sandstone whose bold rugged outlines could not possibly have withstood the passage of an ice sheet (Fig. 292). This small region, therefore, gives an excellent idea of the kind of topography which the whole upper Mississippi Valley would have shown had it not been for the glaciation. At no time did the Labradorean ice sheet spread far enough westward, or the Keewatin sheet far enough eastward, to cover this driftless area. The highland district just south of Lake Superior doubtless served to deflect and weaken the flow of the Labradorean ice which otherwise might have spread far enough to have covered the driftless area. The broad low basins of Lakes Superior and Michigan also made the glacier-deflection easier.

The probable explanation of the extensive driftless areas in Alaska is that, in spite of the low temperatures which must have prevailed, there was insufficient snow for conversion into glacial ice.

Ice Erosion

Ice, like flowing water, has very little erosive effect unless it is properly supplied with tools. When flowing ice is shod with hard rock fragments the power to erode is often pronounced, because the work of abrasion is mostly accomplished by the rock fragments embedded in the

ice rather than by the soft ice itself. For instance, when the great ice lobe moved up the St. Lawrence Valley (Fig. 289) it was shod with many pieces of hard pre-Cambrian rocks, and the effects of erosion are remarkably well shown in the Thousand Islands region, where successions of great grooves cut in the solid rock may often be seen. A little search will reveal polished and scratched or grooved rock surfaces in almost any part of the glaciated region of the continent (Fig. 286). Hard rock ledges most frequently exhibit glacial marks, and the freshness and hardness of such surface rock proves that the ice eroded all of

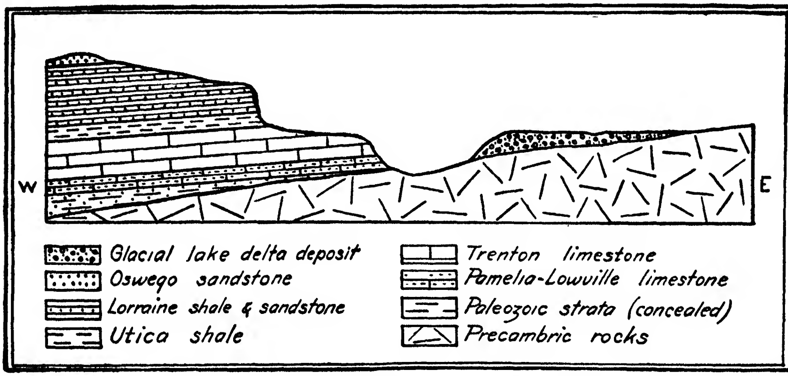


FIG. 291. Structure section across the Black River Valley of northern New York to illustrate the effect of ice erosion and glacial lake deposition. Note the steep front of the shale terrace which has been produced by ice erosion, and the conspicuous delta deposit of the extinct glacial lake on the east side. The surface of the delta deposit represents the former lake level. (After W. J. Miller, N. Y. State Mus., Bul. 135.)

the deep residual soil as well as the zone of rotten rock, and an unknown amount of live or fresh rock (Fig. 286).

In former years a very great erosive power was ascribed to flowing ice, but today some glacialists consider ice erosion to be almost negligible, while many others maintain that, under favorable conditions, flowing ice may produce very notable erosive effects. During the long pre-Glacial time, rock decomposition must have progressed so far that rotten rock, including soils, had accumulated to considerable depths, as today in the southern states. Such soils are called "residual," because they are derived by the decomposition of the very rocks on which they rest. But now one rarely sees rotten rock or soil in its original position well within the glaciated area, because such materials were nearly all scoured off by the passage of the great ice sheet, mixed with other soils and ground up

rock fragments, and deposited elsewhere. Such are called transported soils. Along the southern side of the glaciated area, where the erosive power of the ice was least, rotten rock is more common. Ice, shod with hard rock fragments and flowing through a deep, comparatively narrow valley of soft rock, is especially powerful as an erosive agent, because the tools are supplied, the work to be done is easy, and the increased depth of the ice where crowded into a deep, narrow valley causes greater pressure on the bottom and sides of the channel. Many of the valleys of northern New York were thus favorably situated for ice ero-

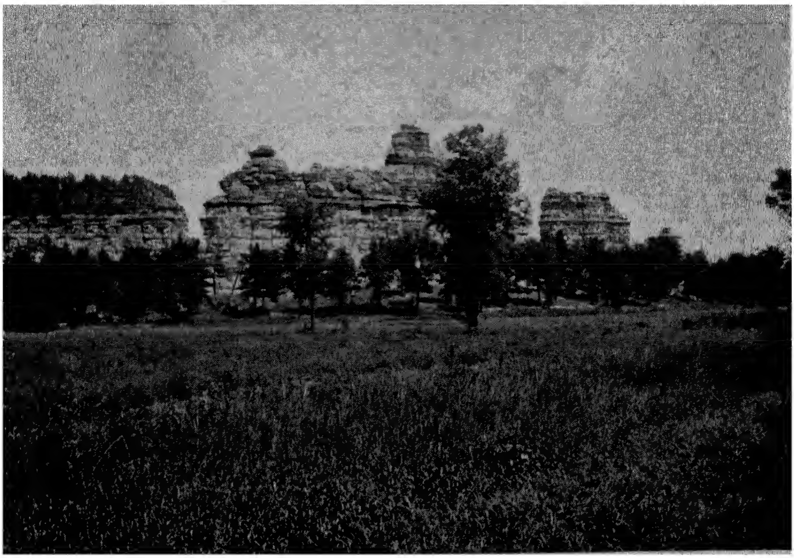


FIG. 292. A large outcrop of sandstone in the driftless area of Wisconsin, near Camp Douglas. The bold, rugged outlines of this mass could not possibly have withstood the passage of an ice sheet.

sion, as, for example, the Champlain, St. Lawrence, Black River, Finger Lakes valleys. The writer has made a special study of ice erosion in the Black River Valley of New York, and Figure 291 is a structure section across it showing the rock terraces and the relations of the various rock formations. The conditions for ice erosion there were unusually favorable, because the ice, in its great sweep around the Adirondacks, was heavily shod with hard rock fragments and entered the deep valley by striking with greatest force against the soft rocks on the west side. The soft shales were worn back more than the harder limestones,

while the very hard pre-Cambrian rocks were but little affected. If soft shales had made up the valley bottom, ice erosion would have caused considerable deepening, as was, no doubt, the case in the valleys of the Finger Lakes region of western New York. Even in places so favorably situated as those just mentioned there is no reason to believe that ice erosion did any more than to modify the profiles of the pre-Glacial valleys.

It is also a singular fact that glacial deposits left by one ice sheet may actually have been overridden by a later advance of ice with little erosion of even such soft material. This probably happened only near

FIG. 293. Sketches showing how the Yosemite Valley, California, region appeared just before and after glaciation. A deep stream-cut canyon, with a conspicuous inner gorge, was changed into a profound U-shaped trough by glacial erosion. Lake Yosemite has since been filled with sediment. *EC,* El Capitan; *YC,* Yosemite Creek; *ND,* North Dome; *HD,* Half Dome; *G,* Glacier Point; *CR,* Cathedral Rocks; *BV,* Bridalveil Creek; and *MR,* Merced River. (After F. E. Matthes, U. S. Geological Survey.)

the margin, where the ice was rather thin and hence did not have much erosive power.

In conclusion we may say that while many comparatively small, local features were produced by ice-sheet erosion, the major topographic features of the great glaciated area were practically unaffected by the abrasive effects of the passing ice sheets.

Local mountain glaciers often produced notable effects in canyons beyond the limits of the great ice sheets, changing their profiles from V-shape to U-shape. There are many excellent examples in Glacier National Park, Rocky Mountain National Park, and in the Cascade-Sierra Nevada Mountains (Fig. 292). An exceptionally fine case in point is Yosemite Valley, California. Just before the Ice Age there was

a stream-cut canyon several thousand feet deep with a prominent inner gorge (Fig. 293, left). Several times during the Ice Age streams of ice (one of them very large) flowed through the canyon. Some of the principal factors favoring glacial erosion were as follows: the great thicknesses of the glaciers (one of them several thousand feet), causing high pressure at the bottom and lower sides; the large number of fragments of hard (granite) rocks with which the glaciers were shod, thus facilitating the work of corrosion; and the existence of numerous, prominent, vertical joints in the granite, thus allowing the plucking action of the glaciers to be very effective in removing extensive joint slabs one after the other from the valley sides. When the last glacier disappeared the great nearly vertical joint faces were left much as we see them today. The lofty waterfalls, including Upper Yosemite Fall (1430 feet high), were formed where post-Glacial streams plunged over the vertical walls. Glacial debris, in the form of a terminal moraine, so blockaded the drainage at the western end of the valley that a lake several hundred feet deep occupied the valley after the ice melted away. The lake was then filled with sediment, and thus the flat, alluviated floor of the present-day valley came into existence. Figure 293 should be studied in connection with the statements just made.

Ice Deposits

The vast amount of debris transported by a great ice sheet was carried either on its surface, frozen within it, or pushed along beneath it. It was heterogeneous material ranging from the finest clay, through sand and gravel, to boulders of many tons' weight. The deposition of these materials took place during both the advance and retreat of the ice, but chiefly during its retreat. Most of the deposits made during the last ice advance were obliterated by ice erosion, while those formed at the time of the retreat have been left intact except for the small amount of post-Glacial erosion and weathering. The term "drift," applied to all deposits of glacial origin, was given at a time when they were regarded as flood or iceberg deposits. Drift covers practically all of the glaciated region except where bare rock is actually exposed, and its thickness is very variable, ranging from nothing to some hundreds of feet.

The ice sheet could advance only when the rate of motion was greater than the rate of melting of the ice front, and vice versa in case of retreat. Thus it is true, though seemingly paradoxical, to assert that

the ice was constantly flowing southward even while the ice front was retreating northward. Whenever, during the great general retreat, the ice front remained stationary because the forward motion was just counterbalanced by the melting, all the ice reaching the margin of the glacier dropped its load to build up a *terminal moraine.* Such a moraine is a more or less distinct ridge of low hills and depressions consisting of very heterogeneous and generally unstratified debris, though at times waters emerging from the ice caused stratification. The depressions are usually called *kettle holes.* The so-called great terminal mo-

FIG. 294. Part of a boulder moraine in the form of a ridge. Near Bakers Mills, Adirondack Mountains, New York.

raine marks the southernmost limit of the ice sheet, and is wonderfully well shown by the ridge of low, irregular hills extending the whole length of Long Island. It is also more or less clearly traceable across the United States, where it marks the southernmost limit of glaciation. Terminal moraines farther northward are generally not so long or sharply defined, though many have been located and described. These are either terminal moraines found at the southernmost limits of ice sheets which did not extend as far south as earlier sheets, or *recessional moraines* formed during each considerable pause of a waning or northward retreating ice sheet.

When the ice front paused for a considerable time upon a rather

flat surface, the debris-laden streams emerging from the ice formed what is called an *overwash plain* by depositing layers of sediment over the flat surface. An excellent illustration of such an overwash plain is all of that part of Long Island lying just south of the great terminal moraine, and known as the Jamaica plain toward the west.

When the ice front extended across a more rugged country, with valleys sloping away from the ice, the large glacial streams, heavy-laden with debris, caused more or less deposition of material on the valley

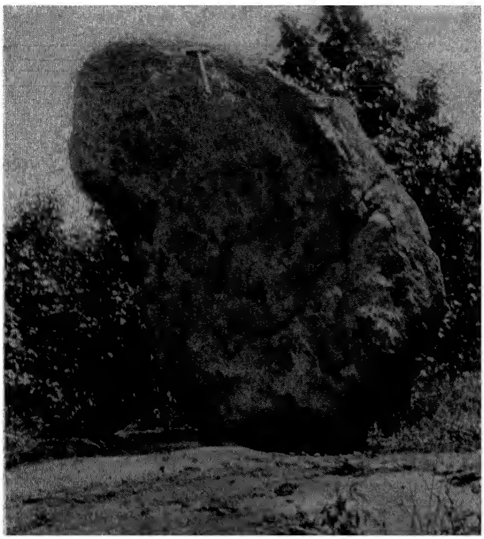


FIG. 295. A remarkably balanced glacial boulder 8 feet high on top of a mountain 2600 feet above sea level and 1000 feet above adjacent valleys. Five miles northwest of Garnet, Adirondack Mountains, New York.

bottoms, often for many miles beyond the ice front. Such deposits, known as *valley trains*, are especially well developed along many of the larger south-flowing streams of the glaciated area.

Glacial boulders (erratics) have already been referred to. They are simply blocks of rock or boulders from the top of the ice or within it which have been left strewn over the country as a result of the melting of the ice. They vary in size from small pebbles to those of many tons' weight, and are naturally most commonly derived from the harder and more resistant rock formations. Thus erratics from the Adirondack Mountains are very numerous from central to southern New York. Erratics are often found high up on the mountains, where they have

sometimes been left stranded in remarkably balanced positions (Fig. 295).

A very extensive glacial deposit, called the *ground moraine,* is simply the heterogeneous, typically unstratified debris from the bottom of the ice which was deposited, sometimes during the ice advance, but most often during its melting and retreat. When it is mostly very fine material with pebbles or boulders scattered through its mass, it is known as *till* or *boulder clay* (Fig. 302). The pebbles or boulders of the till

FIG. 296. A faceted, polished, and striated glacial boulder from Pennsylvania. (Photo by Harden, U. S. Geological Survey.)

are commonly faceted and striated as a result of having been rubbed against underlying rock formations (Fig. 296).

The upper part of a glacial till, where the finer materials have been weathered to a dark, sticky gumbo or clayey substance, is called *gumbotil.* The dark color is caused by decomposing organic matter.

A type of glacial deposit of unusual interest is the *drumlin,* which is in reality only a special form of ground moraine material. The typical drumlins of western New York, Wisconsin, and western Massachusetts are low, rounded mounds of till with elliptical bases and steeper slopes on the north sides. Their long axes are parallel to what was the direction of ice movement (see Fig. 299). In height they rarely exceed 200 feet, being most often less than 100 feet. The origin of the drumlins has not yet been satisfactorily determined, though it is known that they

formed near the margin of the ice either by the erosion of an earlier drift layer or by accumulation beneath the ice under peculiarly favorable

FIG. 297. Part of the glacial-drift plain left by the last (Wisconsin) ice sheet near West Bend in northwestern Iowa. It has been very little affected by erosion. (After Iowa Geological Survey.)

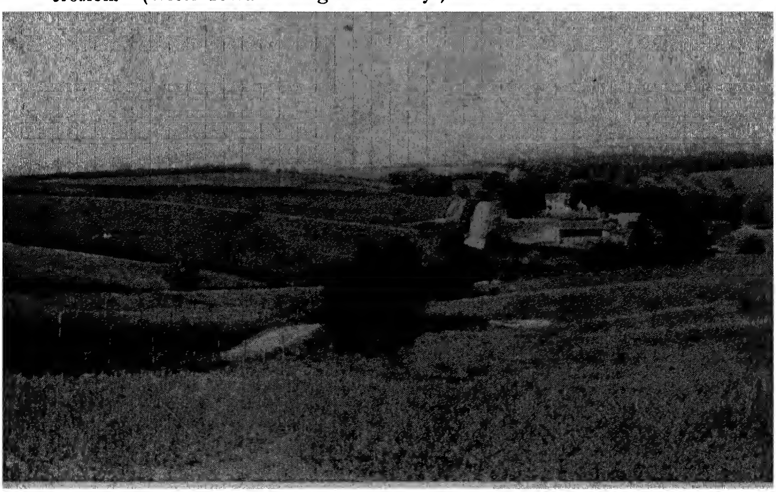


FIG. 298. A region showing glacial drift left by an older (Kansan) ice sheet and since then stream-dissected into a hilly country. Washington County, Iowa. (After Iowa Geological Survey.)

conditions, as perhaps along longitudinal crevasses or fissures. Two of the finest and most extensive exhibitions of drumlins in the world are in

New York, between Syracuse and Rochester, and in eastern Wisconsin, where thousands of them rise above the general level of the plains and give rise to a unique topography.

Another type of glacial deposit in the low hill form is the *kame*, which, in contrast with the drumlin, always consists of stratified drift. Kames are seldom as much as 200 feet high, and typically they have nearly circular bases, though frequently they are of very irregular shapes. At times they exist as isolated hills or in small groups (Fig. 300), while often they are associated with the unstratified deposits of

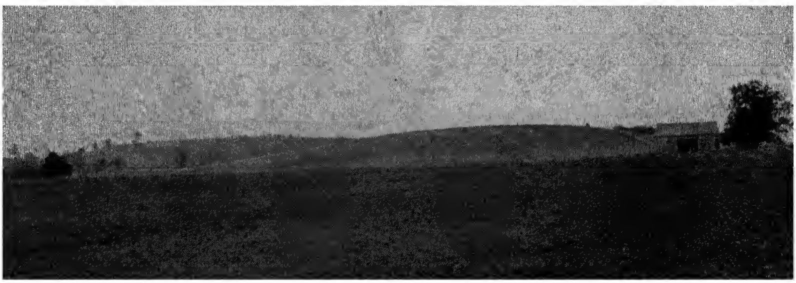


FIG. 299. Typical drumlins (side view) in western New York. (After H. L. Fairchild, N. Y. State Mus., Bul. 111.)

the moraines. When grouped, deep depressions occur between the hills to form what is called the knob and kettle structure. Kames were formed at or near the margin of the retreating ice, and so are found in all parts of the glaciated area, but more especially where there is considerable relief, as in New York and New England. They most generally are located in valley bottoms, but sometimes on hillsides or even hilltops. They are especially abundant along the line of the great terminal moraine (e.g. Long Island) and along the lines of the more important recessional moraines. They were formed as deposits by debris-laden streams emerging from the margin of the ice, the water sometimes having risen like great fountains because of pressure. Such deposits are now actually in process of formation along the edge of the great Malaspina glacier of Alaska.

Eskers are relatively long, low, winding ridges consisting mainly of stratified glacial material (Fig. 301). They are seldom more than a mile long and 75 or 100 feet high. They were formed in streams, overloaded with glacial debris, either in channels on glaciers, or in tunnels beneath the ice.

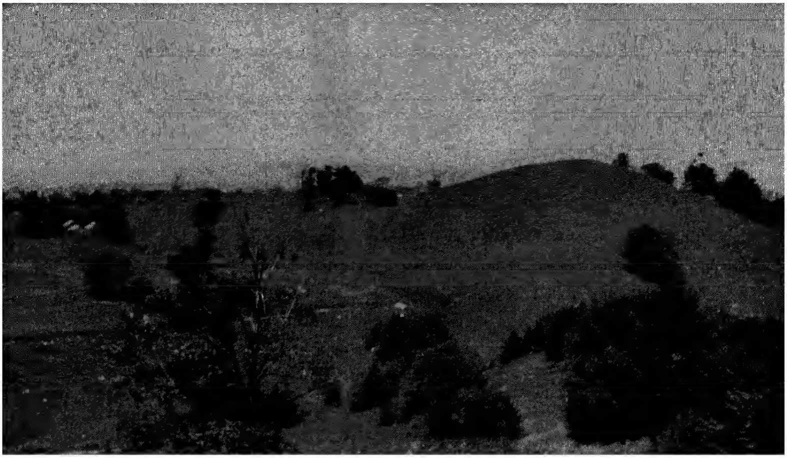


FIG. 300. A group of kames near Remsen, New York.

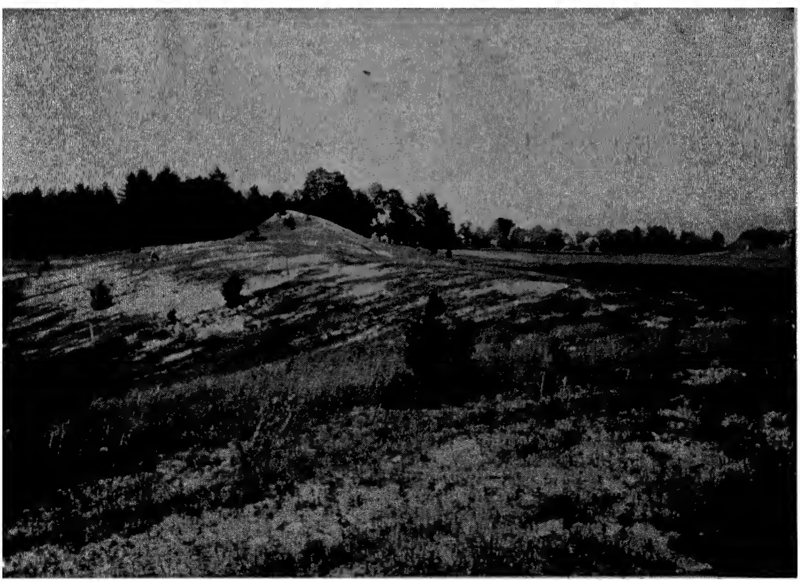


FIG. 301. Part of an esker near Schroon Lake, Adirondack Mountains, New York.

During the ice retreat *glacial lakes* were numerous, particularly where the north-sloping valleys were dammed by the ice, thus ponding the waters in the valleys. Some materials were directly deposited from the glacier in those lakes, but more was brought in by debris-laden streams flowing from the land already freed from the ice. Such glacial lakes and their deposits were common and of unusual interest, but they will be described under a subsequent heading.

In conclusion we may say that the deposition of glacial materials, like glacial erosion, has not changed the major topographic features of

FIG. 302. An exposure of unstratified glacial drift or till containing many boulders. Fifteen miles east of North Bay, Ontario, Canada.

the glaciated region except where surfaces were nearly featureless to begin with. The general tendency of ice deposits has been to fill, or partially fill, depressions and thus to diminish the ruggedness of the topography.

THE LOESS DEPOSITS

Loess deposits are widespread over much of the region from eastern Nebraska, across Iowa, Illinois, and Indiana. Its distribution is rather largely independent of topography. Typically it is a soft, buff to yellowish-brown, very fine grained, sandy clay which seldom shows signs of

stratification. Its thickness usually varies from 10 to 100 feet. Where eroded or cut into, the loess exhibits a remarkable tendency to stand in perpendicular cliffs, sometimes with suggestions of a sort of columnar structure. It was once known as the Bluff formation. Most of it is now known as the Peorian loess (Fig. 302). It is remarkably free from coarse materials, except for certain carbonate of lime and oxide of iron concretions and fossils, the latter being chiefly shells of land gastropods. Most of the loess was deposited during an early Wisconsin sub-stage, because it rests upon the eroded and weathered surfaces of

FIG. 303. An exposure of loess of interglacial (Peorian) age showing a crude columnar structure. Missouri Valley, Iowa. (After W. C. Alden, U. S. Geological Survey.)

older glacial deposits, including those of the Iowan sub-stage, and often passes under later Wisconsin deposits (Fig. 290).

The question as to whether the loess was of aqueous or eolian origin has long been discussed. "In part the loess seems to have been washed from glacial waste and spread in sluggish glacial waters, and in part to have been distributed by the wind from plains of aggrading glacial streams" (W. H. Norton).

GREAT LAKES HISTORY

The Great Lakes certainly did not exist before the Ice Age, but instead the depressions in that region were occupied by streams. During the very long erosion period from the Paleozoic to the Cenozoic, no lakes of any consequence could have persisted. Compared with such an immense length of time lakes are, at most, only ephemeral features of the earth's surface because they are soon destroyed either by being filled

with sediments, or by having their outlets cut down, or both. Since the Great Lakes are of post-Glacial origin it is, then, proper to ask how they came into existence. During pre-Glacial time broad valleys were cut out along belts of weak rock in the Great Lakes region, and these old valleys, to a considerable extent at least, account for the present depressions, but not for the closed lake basins. This idea of pre-Glacial stream valleys is not at all opposed by the fact that some of the lake bottoms are now well below sea level, because there have been notable subsidence of the region since pre-Glacial time and some deepening by ice erosion during the Ice Age. The surface of Lake Erie is 573 feet, and its deepest point 369 feet, above sea level, while the surface of Lake Ontario is 247 feet above, and its deepest point is 491 feet below, sea level. The greatest depth (738 feet) of Lake Ontario is well toward the east end not far from the south shore, and if we consider this deep place as due to pre-Glacial erosion, we ought to find an outlet channel. But no such outlet channel exists because the whole east end, at least, of the lake is rock-rimmed. As Tarr has said: "There could hardly be a valley over 700 feet deep and broad enough to form the continuation of the pre-Glacial Ontario Valley, which is so completely obscured by drift that not the least trace of it has been found on the surface." To assume that this deep part of the basin was formed by warping of the land is not borne out by examining the exposed strata on all sides. It therefore seems quite certain that the pre-Glacial Ontario depression was considerably deepened by ice erosion. The conditions were very favorable for such erosion because the rocks were chiefly soft Ordovician shales; because the ice flowed through a deep pre-Glacial valley; and because there was an unusual crowding of the ice into this valley due to pronounced deflection of a great ice current around the Adirondacks on the west side. Strong arguments might be adduced to show that by ice erosion portions, at least, of all the lake basins were appreciably deepened. Even so, however, we have not yet accounted for the present closed basins. Probably the two most important phenomena which have contributed to the formation of the closed basins of the Great Lakes are (1) the great drift accumulations along the south side and (2) the tilting of the land downward on the north side of the region. The deep drift deposits must certainly have been very effective in damming up the south or southwest-flowing pre-Glacial streams of the region. A great dumping ground of ice-transported materials from the north was in general along the southern side of the Great Lakes and southward. Late in the Ice Age the land on the northern side of

the Great Lakes region was lower than it is today, as proved by the tilted position of certain well-known beaches of extinct lakes (see below). Such a differential tilting or warping of the land must have helped to form the closed basins by tending to stop the southward or southwestward drainage from the region. To summarize, we may say that the present Great Lakes basins resulted from a combination of factors, the more important of which were: (1) the formation of pre-Glacial valleys by stream erosion; (2) a more or less deepening of these valleys by ice erosion; (3) the great accumulation of glacial debris along the

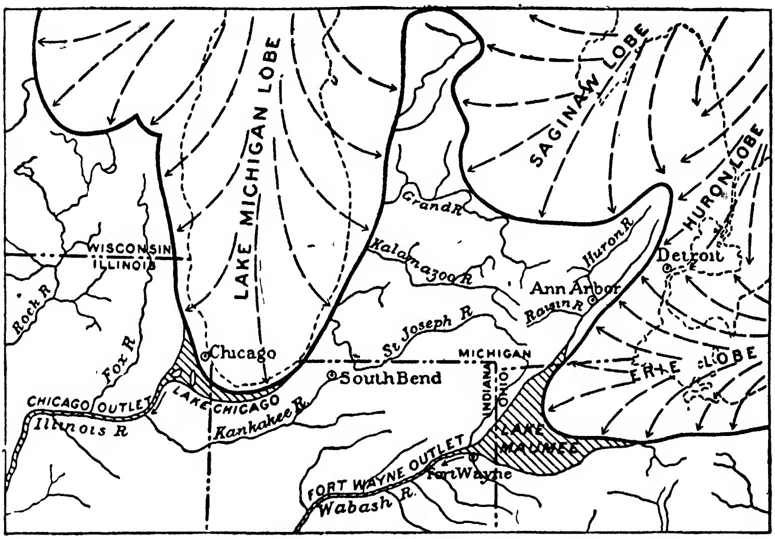


FIG. 304. First stage in the history of the Great Lakes. Note the small ice-front lakes (Maumee and Chicago). (After U. S. Geological Survey.)

southern side of the Great Lakes district; and (4) the tilting of the land relatively downward toward the north during the Ice Age.

We are now ready to trace out the principal stages in the history of the Great Lakes region during the final retreat of the great ice sheet. When the ice front had receded far enough northward to uncover the southern end of Lake Michigan, and an area west of the present end of Lake Erie, small lakes were formed against the ice walls (see Fig. 304). The first of these has been called Lake Chicago, which drained past Chicago through the Illinois River and into the Mississippi; and the second, Lake Maumee, which drained southwestward past Fort Wayne through the Wabash River and thence into the Ohio and Mississippi.

At a later stage the conditions shown on map Fig. 305 existed. Lake Chicago was then larger, and Lake Maumee had expanded into the extensive Lake Whittlesey, which covered nearly all of the area of Lake Erie as well as some of the surrounding country. Lake Whittlesey was at a lower level than the former Maumee, and the outlet past Fort Wayne ceased, but the drainage from Whittlesey was westward by a large river flowing through small Lake Saginaw and into Lake Chicago, which latter still emptied through the Illinois River.

At a still later stage (Fig. 306) Lake Saginaw merged with the waters of the Erie Basin to form the large Lake Warren which ex-

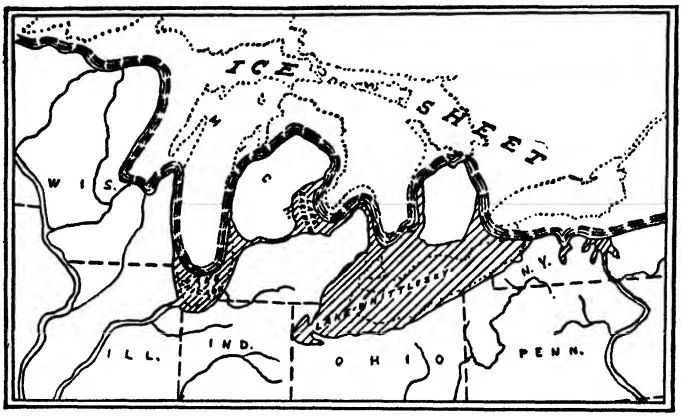


FIG. 305. Lake Whittlesey stage of the Great Lakes history, when the eastern and western ice-margin lakes combined with outlet past Chicago. (Redrawn after Taylor and Leverett.)

tended along the ice front eastward nearly to central New York. As the map clearly shows, the Finger Lakes Basins of New York were then occupied by Warren waters, while Niagara Falls were not then in existence, because that region was also covered by Lake Warren. Lake Warren continued to discharge westward until a very late stage followed by the Lake Lundy level (see Fig. 307), when the waters had worked their way along the border of the Ontario ice lobe into the Mohawk Valley of New York, which was then occupied by a large glacial lake (held up by the Ontario ice lobe on the west and the Champlain-Hudson lobe on the east), and then into the Hudson Valley. Thus, for the first time, the Great Lakes drainage passed eastward into the Atlantic Ocean. This great volume of water draining eastward was often in the form of distinct streams with the ice front for north wall and the

high land of the Helderberg escarpment for wall on the south. Many of these glacial stream channels, often high up on the hills of central to western New York, are still plainly visible.

By successive stages, due to complete removal of ice from central New York, and a draining of the glacial lake in the Mohawk Valley, the waters fell below the Warren-Lundy levels and Lake Iroquois was formed (see Fig. 308). The old beach line of this lake is still plainly visible in New York. Lake Iroquois covered somewhat more than the present area of Lake Ontario, and the distinctly lower water level here

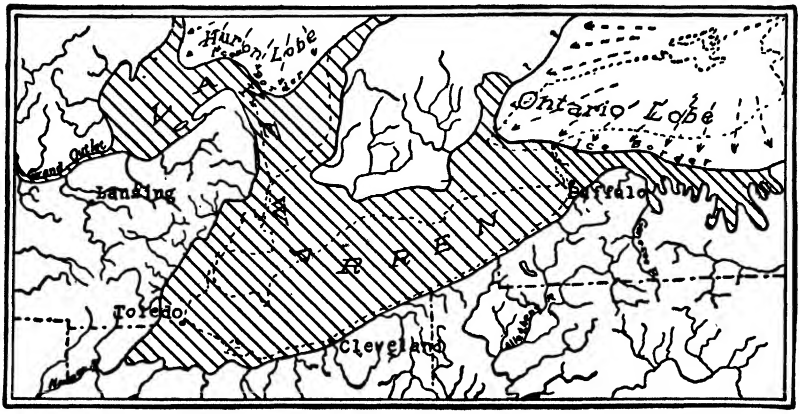


FIG. 306. Glacial Lake Warren. At this stage the discharge of the lake was still westward to Lake Chicago, while the eastern end of the lake covered most of the Finger Lakes region of New York. (Redrawn after Taylor and Leverett.)

than in the Erie Basin allowed the modern Niagara River to begin its history by flowing northward over the limestone plain near Buffalo. Meantime the waters of the upper lake basins had merged to form Lake Algonquin, which at first probably discharged past Detroit through the Erie Basin and into Lake Iroquois by way of Niagara River. Later, however, when the ice had withdrawn a little farther northward, a lower outlet was formed through the Trent River by which Lake Algonquin drained into Lake Iroquois. The old Trent River channel is now higher than the Detroit outlet, but some of the proofs for the former Trent outlet are as follows: (1) The presence there of a large, distinct river channel; (2) the convergence of the beaches toward that channel; and (3) the fact that the land was then considerably lower on the north or northeast side of Lakes Ontario and Erie than on the

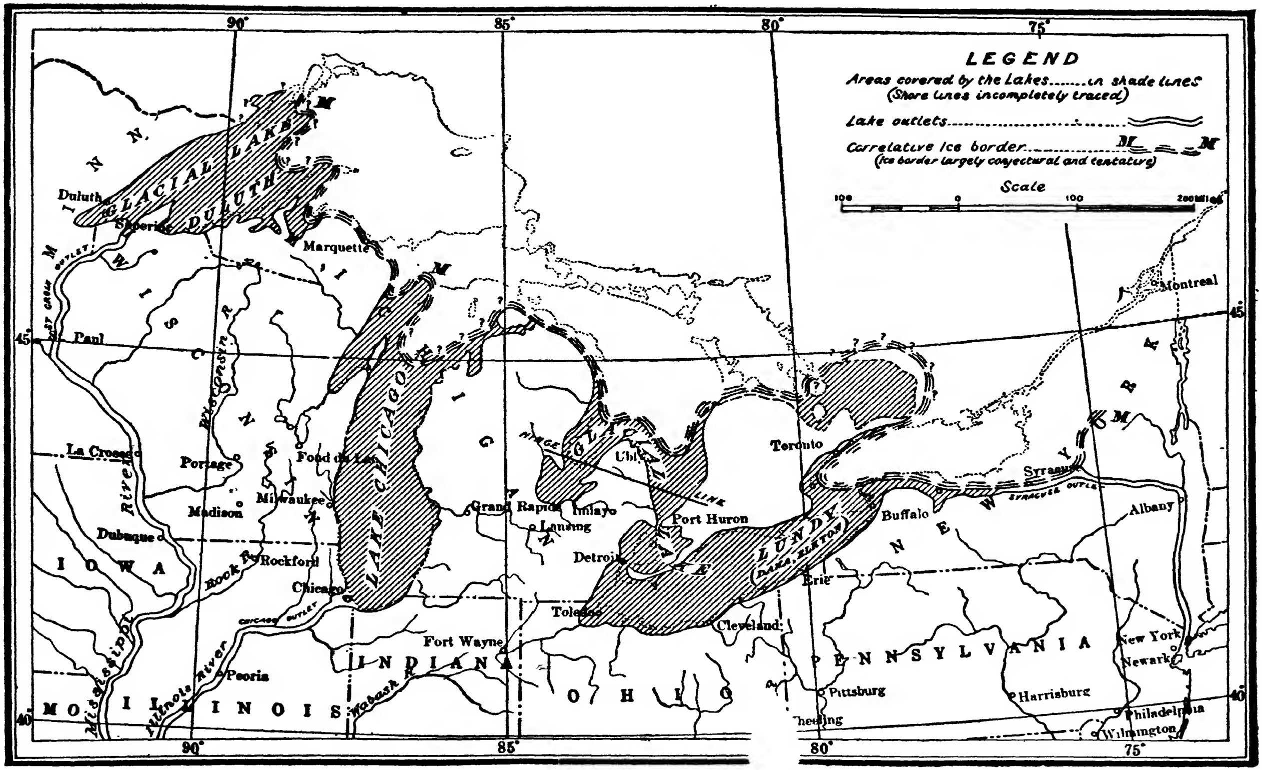


FIG. 307. Glacial Lakes Duluth, Chicago and Lundy. Note the drainag of the western lakes into the Mississippi River, and the eastern lakes into the Hudson Valley. (After Taylor and Leverett, courtesy of The Smithsonian Institution.)

south side. For example, in following the old Iroquois beach we find that it gradually rises to higher levels until it is several hundred feet higher at the east than near the mouth of Niagara River. This tilting of the beach has been due to warping of the land since the lake existed, and it is evident therefore that during the Algonquin-Iroquois stage the Trent River channel was lower than that past Detroit. During the Algonquin-Iroquois stage the waters of all the Great Lakes region discharged through the Mohawk-Hudson valleys, and the volume of water which flowed through the Mohawk Valley must have been as great as,

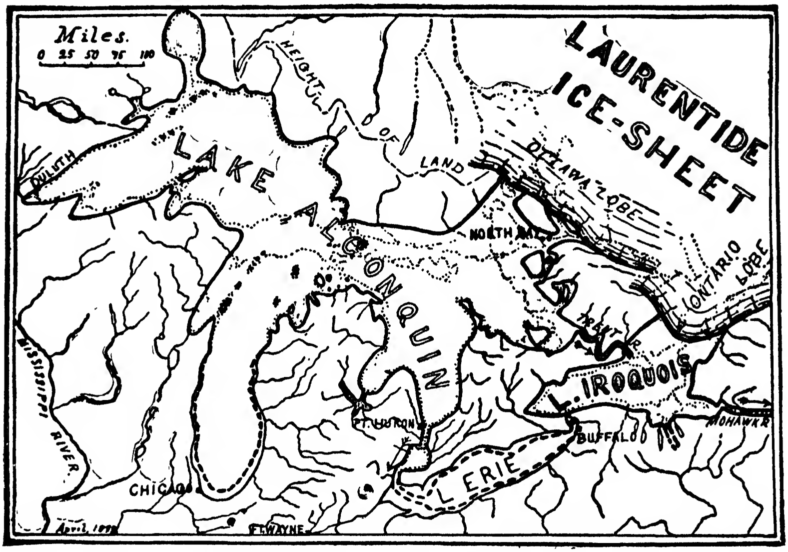


FIG. 308. The Algonquin-Iroquois stage of the Great Lakes, with outlet through the Mohawk-Hudson Valleys of New York. (After Taylor, courtesy of the New York State Museum.)

if not greater than, that which now goes over Niagara Falls. During this time the St. Lawrence Valley was still buried under ice.

Still later the ice withdrew enough to allow the Algonquin-Iroquois waters to discharge along the northern base of the Adirondacks and into what appears to have been ice-ponded waters in the Champlain Basin, and thence into the Hudson Valley. The Mohawk Valley outlet was thus abandoned.

Finally the ice withdrew far enough to free the St. Lawrence Valley when the waters of the Great Lakes region dropped to a still lower level, bringing about the Nipissing Great Lakes stage (see Fig. 309).

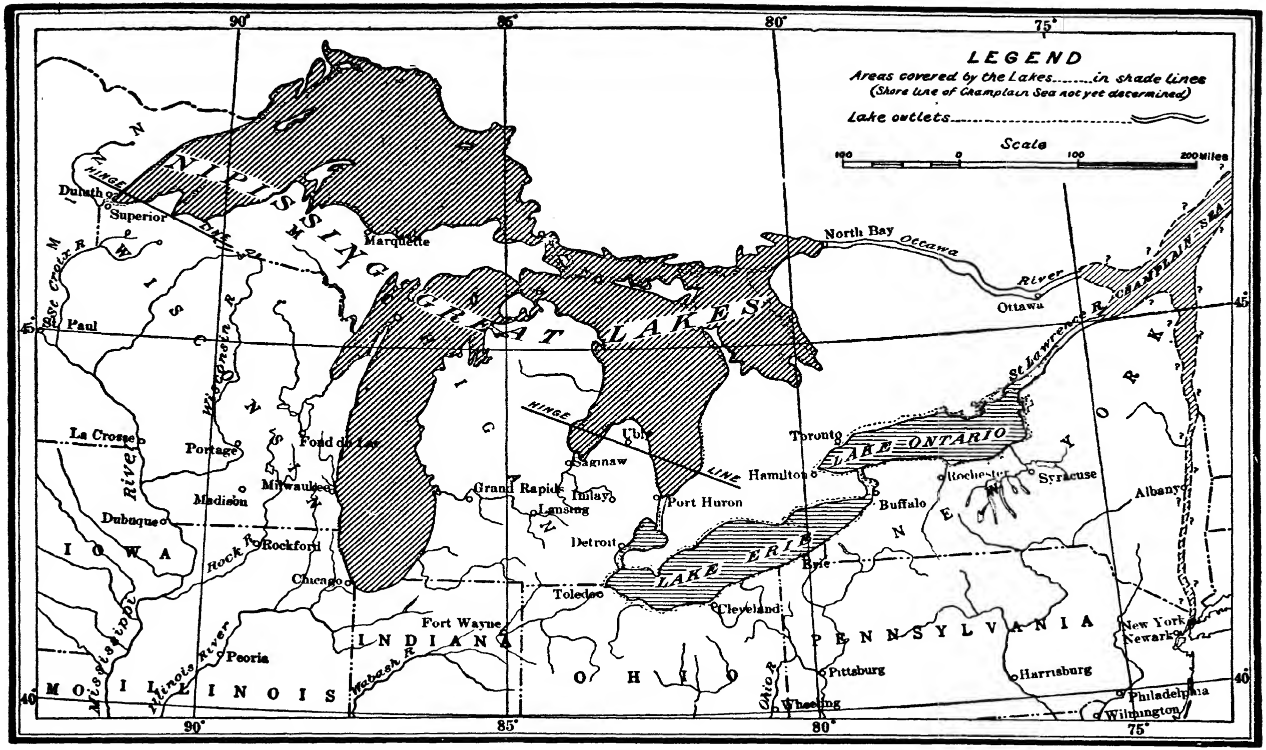


FIG. 309. The Nipissing Great Lakes and their correlatives. The oblique-lined area on the east was occupied by tide-water (Champlain sea), but the boundary lines are not yet very definitely known. (After Taylor and Leverett, courtesy of The Smithsonian Institution.)

The Nipissing Lakes found a low outlet through the Ottawa River (then free from ice) and into the Champlain arm of the sea. Post-Glacial warping of the land brought the Great Lakes region into the present condition, but this, and the Champlain subsidence, being really post-Glacial features, will be described below.

Other Existing Lakes and Their Origin

Counting all, from the smallest to the largest, there are within the glaciated area of North America tens of thousands of lakes, and these

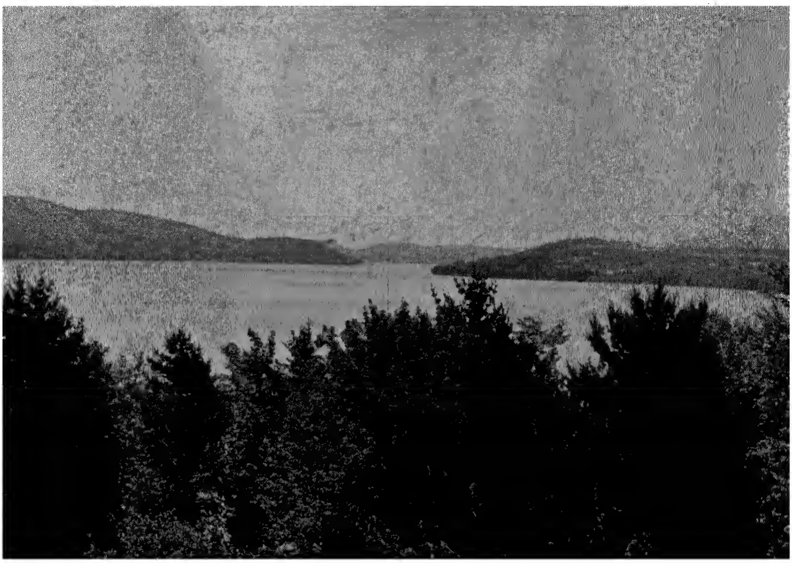


Fig. 310. An example of a glacial lake occupying part of a former river valley. It is a remnant of the once much longer glacial lake shown in Figure 311. Schroon Lake, Adirondack Mountains, New York.

constitute one of the most striking differences between the geography of the present and that of pre-Glacial time. These lakes are widely scattered, though in the United States they are most abundant in the regions of greater relief, such as Maine, New Hampshire, New York, and Minnesota, because lake basins were more readily formed by drift dams across the deeper pre-Glacial valleys of those regions.

It is well known that most of the larger lakes, especially those of the linear type, occupy portions of pre-Glacial stream channels. All the existing lakes are due, either directly or indirectly, to glacial action.

Among the ways by which such bodies of water may be formed are these: (1) by building dams of glacial drift across old river channels; (2) by ice erosion; and (3) by accumulation of water in the numerous depressions which were formed by irregular deposition of the drift (kettle-holes, etc.). Hundreds of small lakes, often not more than mere pools in size, belong to the last-named type, while very many of the large and small lakes are due chiefly to the existence of drift dams. Certain lakes in southeastern Canada and elsewhere appear to occupy rock basins scoured out by ice erosion.

In considering the origin of glacial lakes, the so-called Finger Lakes of central-western New York deserve special mention. All are agreed that the lakes of this remarkable group occupy pre-Glacial valleys, most or all of which contained north-flowing streams. These lakes have dams of glacial drift across their lower (north) ends, and the dams have been important factors in the formation of the lakes, being in some cases perhaps the sole cause. But in the cases of the two largest lakes—Seneca and Cayuga—there is strong evidence, from the hanging valley character of the tributaries, that the pre-Glacial valleys were notably deepened by ice erosion.

The presence of Lake Champlain is due principally to a combination of factors, including late elevation of the land, with greater uplift on the north; heavy glacial accumulations toward the north; and possibly some deepening as a result of ice erosion.

In the basin of Lake George there was a pre-Glacial divide where the "Narrows" are now located, and this divide appears to have been considerably lowered by ice erosion when part of the Champlain ice lobe ploughed its way through the deep, narrow valley. The waters are now held in by a drift dam at each end.

Well within the glaciated region of the interior of the continent the history of Lake Winnipeg is of special interest, but since this lake is merely a remnant of a former much larger body of water, it will be described in connection with extinct glacial lakes.

Extinct Glacial Lakes

The beds of thousands of extinct glacial lakes are known to be scattered over the glaciated area. Some of these existed only during the time of the ice retreat, while others persisted for a greater or lesser length of time after the Ice Age. Lakes Chicago, Iroquois, etc., already described, were fine examples of the first type. North-sloping valleys were particularly favorable for the development of glacial lakes during

the retreat of the ice, because the ice front always acted as a dam across such valleys, thus causing the waters to become ponded. Among the best criteria for the recognition of these extinct glacial lakes are typical, flat-topped, delta deposits, formed by inflowing streams, and distinct beaches (Fig. 291).

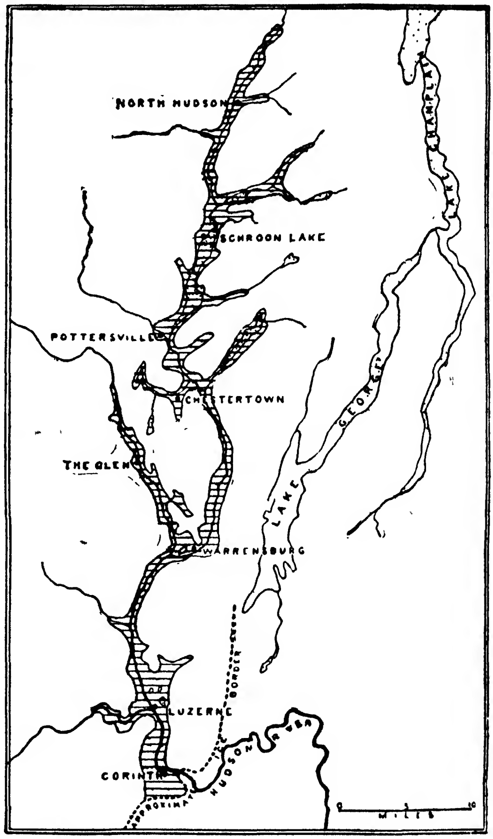


FIG. 311. Glacial Lake Warrensburg in the southeastern Adirondack Mountains of New York. The position of the border of the glacier, which acted as a dam, is indicated. Dotted areas are existing lakes. (After W. J. Miller, Bul. Geol. Soc. Amer., Vol. 36, 1925.)

A good example of the many glacial lakes which existed only when the waning ice sheet was present, acting as a dam to pond the waters, was Lake Warrensburg, situated in the southeastern Adirondack region of New York. This lake, which lay in parts of the Hudson and Schroon River valleys, was remarkably long (70 miles) and narrow (see map, Fig. 311). Delta terraces and wide sand flats, marking the bed of the former lake, are finely preserved. These deposits are several hundred feet higher at the north than at the south because of post-Glacial tilting of the land of the general region. The map shows the approximate position of the ice-border dam when the Lake George and Lake Champlain basins were still occupied by the glacier. Several remnants of the glacial lake still remain as shown by the dotted areas within the ruled areas.

A fine example of a very large glacial lake in the interior of North America, and now represented only by remnants (e.g. Lake Winnipeg),

has been called Lake Agassiz in honor of the discoverer of the fact of the Quaternary Ice Age. This lake, fully 700 miles long and several hundred miles wide, extended over the whole valley of the Red River of the North in North Dakota and Minnesota, and northward over much of Manitoba. It covered a larger area than the combined Great Lakes. Its water was held up by the united fronts of the Keewatin and Labradorean ice sheets as they retreated northward. Its outlet was southward through the Minnesota and Mississippi Rivers until the ice melted back (northward) far enough to open the outlet by way of Nelson River to Hudson Bay, when the great body of water was rapidly lowered, leaving only the present-day remnants, principally Lake Winnipeg. The soil of this smooth old lake bed is wonderfully rich.

Drainage Changes Caused by the Glaciation

In addition to its lakes, the glaciated area is also characterized by numerous gorges and waterfalls, which are largely indirect effects of glaciation. As a result of the very long time of pre-Glacial erosion, it is certain that typical, steep-sided, narrow gorges, as well as waterfalls, must have been very uncommon, if present at all.

During the Ice Age many of the valleys were more or less filled with glacial drift so that post-Glacial streams were often forced to find different courses where they cut new valleys, sometimes in the form of gorges in hard rock. A few fine examples are Watkins Glen, Trenton Chasm, and Ausable Chasm in New York, and the Dells of the Wisconsin River. Like lakes, such features are ephemeral, because, under our conditions of climate, gorges soon (geologically) widen at the top, and waterfalls disappear by retreat or by wearing away the hard rock which causes them.

Changes of stream courses are also numerous in many parts of the glaciated territory. It is the present purpose to describe only a few typical, well-studied cases of such stream changes.

In the southeastern Adirondack Mountains certain important principles of drainage changes due to glaciation are illustrated by the upper waters of the Hudson River. The accompanying sketch map (Fig. 312) gives an idea of the changes. Near Warrensburg the Hudson River was deflected westward from its pre-Glacial channel because of the presence of a lobe of the waning ice sheet in the Lake George depression. At Corinth and Northampton, respectively, the Hudson and Sacandaga rivers show remarkable eastward deflections instead of fol-

lowing broad, deep pre-Glacial valleys southward into the Mohawk Valley. These deflections were caused by heavy morainic deposits acting as dams across the valleys south of Corinth and Northampton.

The world-famous Niagara Falls and Gorge are wholly post-Glacial in origin. After plunging 165 feet at the falls, the river rushes for 7 miles through the gorge, whose depth is between 200 and 300 feet. When the glacial waters in the eastern Great Lakes region had dropped to the Iroquois level, the Niagara limestone terrace in the vicinity of Buffalo, and with steep escarpment or northern front at Lewiston and Queenston, ceased to be covered with lake water, and the Niagara River came into existence by flowing northward over this limestone plain. The river first plunged over the escarpment at Lewiston, thus inaugurating the falls there. Since that time the falls have receded the 7 miles up stream to their present position. Soft shales underlie the layer of harder Niagara limestone, and the recession of the falls has clearly been caused by the breaking off of blocks of limestone due to undermining of the soft shales. A glance at the map (Fig. 314) will show that the gorge development is really taking place on the Horseshoe Falls side, where the volume of water is much greater, and that in a short time, geologically considered, the American Falls will be dry.

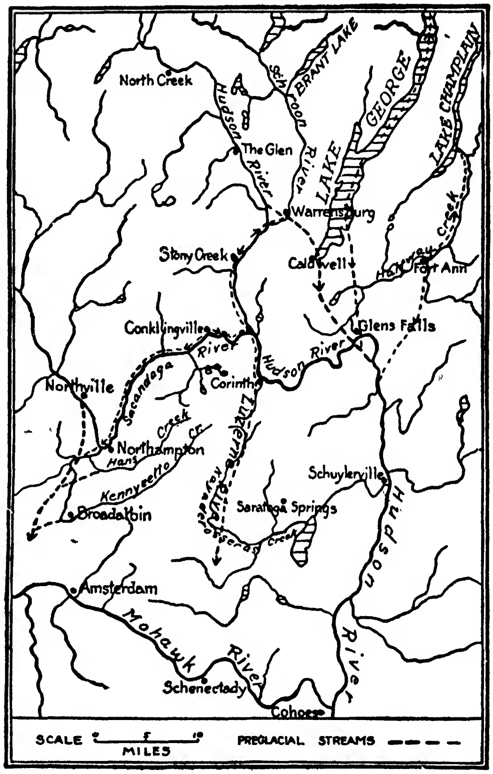


FIG. 312. Sketch map of the southeastern Adirondack region, showing the relation of the pre-Glacial drainage to that of the present. Pre-Glacial courses shown by dotted lines only where essentially different from present streams. (After W. J. Miller, Bul. Geol. Soc. Amer., Vol. 22.)

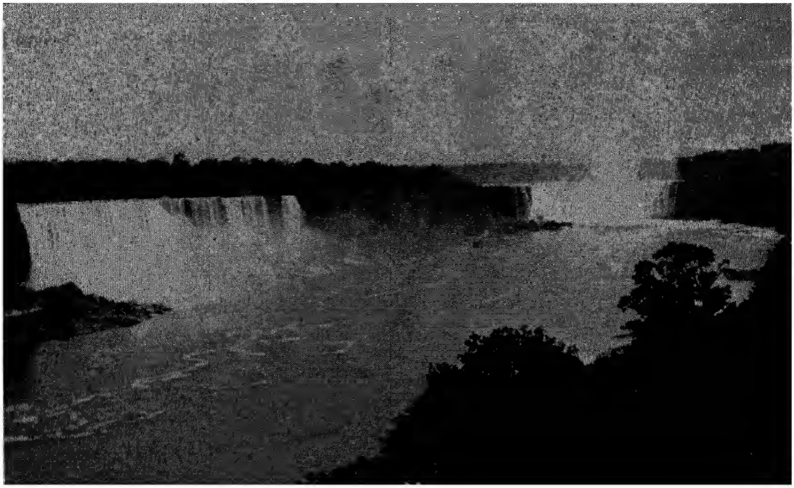


FIG. 313. Niagara Falls and part of Niagara Gorge. American Falls on the left, and Canadian (Horseshoe) Falls on the right. Most of the water by far passes over the Canadian Falls situated at the head of the gorge.

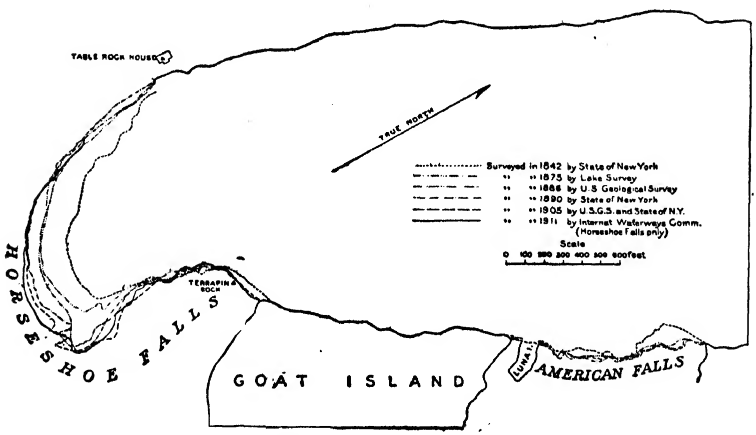


FIG. 314. Map showing the amount of retreat of Niagara Falls between 1842 and 1911. The middle portion of the Horseshoe Falls retreated about 300 feet during this interval. The whole of Niagara Gorge, 7 miles long, has been formed by the retreat of the falls. (After F. B. Taylor, U. S. Geological Survey.)

Another well-studied example of important drainage change is shown by the accompanying map (Fig. 316) of part of northern Illinois. The pre-Glacial Rock River flowed southward into the Illinois River, instead of southwestward into the Mississippi as at present.

FIG. 315. View looking south through part of the Grand Coulee, Washington. This canyon was cut by the diverted Columbia River during a late stage of the Ice Age.

Even such large rivers as the Missouri and the Columbia were sometimes notably shifted out of their pre-Glacial channels by the invasion of the ice sheets. Thus, the Missouri River which formerly followed what is now the James River Valley in eastern South Dakota, was forced many miles westward to its present course across the state. The Cordilleran glacier filled a portion of the valley of the Columbia River in central Washington, forcing the mighty river eastward to find a new course for many miles, where it eroded a canyon called the Grand Coulee. On the melting of the ice, the river returned to its former valley.

The above cited cases are sufficient to illustrate the general principles of drainage modifications due to glaciation, the two chief factors having been (1) actual presence of the ice or (2) heavy drift filling in pre-Glacial valleys.

Changes of Sea Level Caused by the Glaciation

It has been estimated that the melting of the Antarctic glaciers, now covering about 5,000,000 square miles, would cause the level of the sea to rise fully 100 feet. When the greatest Pleistocene glaciers existed, and covered about 10,000,000 square miles, they represented

enough water temporarily removed from the sea to lower its level 250 feet or more. At such times the shorelines of the world were farther out than now, considerable parts of the present continental shelf areas then being land. During interglacial stages the sea level stood at about its present height, or higher by about 100 feet in case the glaciers completely melted away.

Advantages and Disadvantages of Glaciation

Advantages. As a result of late Tertiary stream dissection, much of what is now the glaciated area of the United States had been converted into a fairly rugged country. Because of the heavy accumulations of drift, chiefly in the depressions, this ruggedness was greatly diminished and, in fact, many districts were actually converted into almost featureless plains. Old lake beds (e.g. that of Lake Agassiz) also are usually very smooth. Thus, agricultural pursuits, transportation, and travel have been made easier.

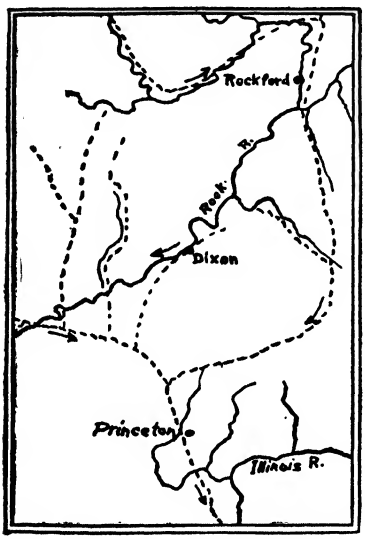


Fig. 316. Pre-Glacial drainage (dotted lines) of a part of northwestern Illinois. (Modified after Leverett.)

Over very extensive areas, such as the upper Mississippi Valley, the soils have been made deeper and richer on the average because the pre-Glacial soils were not only comparatively thin on the numerous hillsides, but also they were sandy or clayey residual materials from which much of the rich (soluble) mineral plant foods had been washed out. The glacial drift soils are usually more uniformly deep and consist of finely ground rocks of many kinds still rich in the soluble plant foods.

Water-power facilities have been vastly increased because of the development of thousands of waterfalls, rapids, and lakes. Pre-Glacial streams were mostly graded and hence without waterfalls or rapids, while pre-Glacial lakes were almost entirely absent. Lakes, by acting as reservoirs, help much in causing a more uniform flow of streams. In many places such reservoir effect is furthered by artificially increasing

the heights of the natural dams, as e.g. in the Adirondacks. Also many large reservoirs can easily be constructed at comparatively little expense by restoring dams of extinct lakes.

Large lakes afford cheap transportation facilities, and often have a tempering influence upon the climate. Many lakes furnish abundant water supplies for towns and cities, as well as more or less fish for food.

The benefit of lakes, waterfalls, gorges, etc., from the aesthetic or scenic standpoint would be difficult to overestimate.

Drift deposits are often used, e.g. clays, for the manufacture of brick, tile, etc., and sand and gravel for various construction purposes.

Disadvantages. In some cases the earth's surface has been increased in ruggedness by the drift accumulations, especially in extensive kame-moraine areas, thus hindering agriculture, transportation, and travel.

In many places, as in parts of New England, New York, and eastern Canada, the cultivation of the soil has been made difficult because of the numerous glacial boulders it contains. In these same regions many of the old lake or other deposits are too sandy or gravelly to be very fertile.

Large areas now covered by lake waters would make valuable farming land. This is particularly true of the Great Lakes.

All things considered, it seems certain that the advantages due to glaciation are notably greater than the disadvantages.

Duration of the Glacial Epoch

Among the most important criteria for estimating the duration of the Glacial epoch are the following: (1) Amount of erosion of the various drift deposits; (2) depth of oxidized zones of drift deposits; (3) amount of decomposition of materials, such as pebbles and boulders; (4) extent of leaching or removal of lime carbonate involved in the formation of gumbotils; (5) amount of vegetable growth during the interglacial intervals; (6) the volumes of the drift deposits; (7) climatic changes indicated by glacial and interglacial faunas and floras; and (8) rates of advance and retreats of glaciers. None of these are subject to very direct or accurate measurement, including the rates of changes, but considered altogether an idea of the order of magnitude of the time involved may be gained.

Some of the criteria, such as rate of development of gumbotil; amount of erosion of the drift deposits, based upon the post-Glacial rate; and rates and retreats of modern glaciers, yield better results than

others. Thus, in view of the fact that the gumbotils of several interglacial stages are 5 to 12 feet thick, it is evident that they indicate long times of weathering. G. F. Kay, using post-Glacial rate of alteration as a standard, has estimated that it took about 70,000 years to develop gumbotil to a depth of 5 feet during the Sangamon interglacial stage, and 250,000 years to form 12 feet of gumbotil during the Yarmouth stage. He also estimated that the interglacial stages were much longer than the glacial stages.

After considering many of the factors involved in the problem, it has been concluded that the Glacial epoch was at least 700,000 years long, and very probably 1,000,000 years or more.

Length of Time Since the Glacial Epoch

Estimates of the length of time since the close of the Ice Age are perhaps more satisfactory, though it must be remembered that the close of the Ice Age was not the same for all places. The ice retreated northward very slowly and when, for example, southern New York was free from the ice, northern New York was still occupied by the glacier. The best estimates of the length of time since the close of the Ice Age are based upon the rate of recession of Niagara Falls. We have learned that Niagara River began its work about the time the glacial waters in the Erie-Ontario basins dropped to the Iroquois level, and that the falls were first formed by the plunging of the river over the limestone escarpment at Lewiston. Studies based upon actual surveys, drawings, daguerreotypes, photographs, etc., made between the years 1842 and 1905, have shown that the Horseshoe Fall had receded about 5 feet a year, while the American Fall, between 1827 and 1905, had receded about 3 inches a year. Thus the gorge cutting is clearly taking place on the Canadian side. The length of the gorge is 7 miles, and if we consider the rate of recession to have been always 5 feet a year, the length of time necessary to cut the gorge would be something over 7000 years. But the problem is not so simple, since we know that at the time of, or shortly after, the beginning of the river, the upper lakes drained out through the Trent River, and then still later through the Ottawa River. So it is evident that, for a good part of the time since the ice retreated from the Niagara region, the volume of water passing over the falls was notably diminished, and hence the length of time for the gorge cutting increased. The best estimates for the length of time since the ice retreated from the Niagara region vary from 10,000 to 40,000 years, an average being about 20,000 years. In a similar way, the time

based upon the recession of St. Anthony's Falls, Minnesota, ranges from about 10,000 to 16,000 years. While closer estimates are practically impossible, it is at least certain that the time since the Ice Age is far less than its duration, and that, for the region of the northern United States, the final ice retreat occurred only a very short (geological) time ago.

When we consider the slight amount of weathering and erosion of the latest glacial drift, we are also forced to conclude that the time since the close of the Ice Age in the United States is to be measured by only some thousands of years. Thus kames, drumlins, extinct lake deltas, and moraines with their kettle holes, have generally been very little affected by erosion since their formation.

Time Since the Climax of the Last Ice Sheet

A way to determine the number of years since the last (Wisconsin) ice sheet reached its climax is to find out how long it took the glacier to recede from its southernmost limit to Niagara Falls, or about 600 miles, and add this figure to the age of the falls.

A fair idea of the rate of recession of the last ice sheet may be gained by counting and correlating the layers of clay which were deposited in lakes in front of the retreating edge of the glacier. Each layer, consisting of a darker and a lighter band, is called a *varve*. Each varve represents the material laid down in one year, the lighter, coarser grained, silty portion during the summer, and the darker, finer grained, greasy portion during the winter. By the use of this method, De Geer found that the last ice sheet in Europe retreated a distance of 270 miles to the northwest of Stockholm in 5000 years, or at the rate of 285 feet per year. Antevs, using the same method, concluded that the last glacier receded a distance of 185 miles in western New England in 4100 years, or at the rate of 240 feet per year. If, therefore, we put the rate of retreat at about 260 feet per year, it took the Wisconsin ice sheet somewhat more than 12,000 years to retreat from its southernmost limit to Niagara Falls. Combining this figure with the average estimate of 20,000 years for the age of Niagara, we get at least a rough approximation of the time since the last (or Wisconsin) glacier reached its climax, or about 32,000 years ago.

The Glacial Epoch in Europe

In many important respects the history of the Quaternary period in Europe is much like that of North America. The accompanying map (Fig. 317) shows the extent (about 2,000,000 square miles) of ice sheet

at the time of maximum glaciation. As the map also shows, the great centre of dispersal was over the Scandinavian peninsula, with apparently a small, secondary centre over Scotland. The ice over Scandinavia is estimated to have been 6000 to 7000 feet deep. The Baltic, North, and Irish Seas were completely filled by the great ice sheet which extended well south into Germany and Russia. As in North America, four major glacial ages, separated by interglacial ages, have been recognized. These with their North American correlatives are: Günz (Nebraskan), Mindel (Kansan), Riss (Illinoian), and Würm (Wisconsin). During the Glacial epoch the glaciers of the Alps were far larger and more numerous than today, and they often flowed down to the lowlands on all sides. The Pyrenees and the Caucasus Mountains were also vigorously glaciated.

As in North America, also, northern Europe was notably higher than now, apparently late in the Tertiary or early in the Quaternary; then, toward the close of the Glacial epoch, there was subsidence (of Scandinavia at least) to below the present level; and this was followed by partial re-elevation of at least some hundreds of feet to the present level. Actual surveys have proved that from central to northern Sweden the land is still rising. The great fiords of Norway, with their raised beaches, testify to the important changes of level above mentioned.

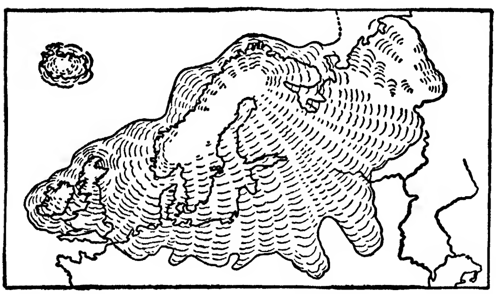


FIG. 317. Map showing the extent of ice in Europe at the time of maximum glaciation. (After J. Geikie, from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

In other continents many of the higher mountains bore glaciers, even where none at all exist today. Also, so far as known, the Antarctic region was heavily glaciated much as it is today.

Cause of the Glaciation

The cause of the glaciation has been a very perplexing problem. Various hypotheses, often of widely different character, have been offered by way of explanation, but there is nothing like general agreement

on the subject. We have here a fine illustration of the difference between "fact" and "hypothesis" which the student of natural science must always keep clearly in mind. Thus, the fact of the Glacial epoch (including much of its history) is conclusively established, but the cause of the glaciation is a matter concerning which we have only hypotheses or speculations.

In this elementary work we can do no more than suggest several of the leading hypotheses. Those further interested in the subject are referred to special articles and larger general works, particularly Chamberlin and Salisbury's "Geology," Vol. 3. One point to be borne in mind is that no hypothesis is required to account for an average yearly temperature of more than 10 or possibly 12 degrees lower than at present over the glaciated area in order to have brought on the Ice Age. Another point is that both sufficient snowfall and low temperature were necessary.

A Geologic (Elevation) Hypothesis. As we have already pointed out, the evidence, chiefly from the submerged river channels along the Atlantic Coast, clearly indicates greater altitude of northeastern North America late in the Tertiary and probably also in the early Quaternary. An altitude several thousand feet greater than now has been claimed for this region. Since it is well known that the temperature becomes lower with increasing altitude (one degree for about 300 feet), it has been argued that the greater altitude of the glaciated area was in itself sufficient cause for the glaciation. "Northern elevation produced ice-accumulation; ice-accumulation by weight produced subsidence; subsidence produced moderation of temperature and melting of ice; and this last by lightening of load produced re-elevation" (J. Le Conte). It is not necessary to assume that maximum elevation and ice-accumulation were coincident, because an effect often lags behind its cause. This northern elevation also is believed to have sufficiently upraised the northern ocean basins to cut off warm currents, like the Gulf Stream, thereby depriving the northern lands of such warming influences.

It has been urged against this hypothesis that there is no positive evidence for nearly as much as several thousand feet of elevation of the glaciated region; that it is not at all proved that the northern elevation occurred at the proper time to produce glaciation; and that the only way glacial and interglacial stages could be accounted for would be by the unreasonable assumption of repeated elevation and subsidence corresponding to each advance and retreat of the ice.

Chamberlin's Atmospheric Hypothesis. Among the atmospheric hypotheses, the one which Chamberlin has put into its best form "is based chiefly on a postulated variation in the constituents of the atmosphere, especially in the amount of carbon dioxide and water. Both these elements have high capacities for absorbing heat, and both are being constantly supplied and constantly consumed. . . . The great elevation of the land at the close of the Tertiary seems to afford conditions favorable both for the consumption of carbon dioxide in large quantities, and for the reduction of the water content of the air. Depletion of these heat-absorbing elements was equivalent to the thinning of the thermal blanket which they constitute. If it was thinned, the temperature was reduced, and this would further decrease the amount of water vapor held in the air. The effect would thus be cumulative. The elevation and extension of the land would also produce its own effects on the prevailing winds and in other ways, so that some of the features of the hypsometric (elevation) hypothesis form a part of this hypothesis. . . . By variations in the consumption of carbon dioxide, especially in its absorption and escape from the ocean, the hypothesis attempts to explain the periodicity of glaciation. Localization (of glaciation) is attributed to the two great areas of permanent low pressure in proximity to which the ice sheets developed."[1]

Huntington's Sunspot Hypothesis. It seems to be a well-established fact that the temperature of the air near the earth's surface is lower at times of unusual sunspot activity. The intensity of sun's heat coming to the earth is known to vary as much as 3 to 5 per cent during short periods, ranging from a few days to a few weeks. Huntington has suggested that the several real glacial epochs of known geological time may have occurred during periods of exceptionally great and long sunspot activity, probably in combination with other factors. During such a cycle of very intense solar activity, not only would the earth's winds be stronger and hence conduct more heat upward from the earth's surface, but also these stronger winds would cause the great eastward moving storm areas (or cyclonic storms) to travel farther north than they do at present in both North America and Europe. The lowering of the temperature and the increase in atmospheric moisture, resulting from the conditions just mentioned, would explain the gathering of the great Pleistocene glaciers.

[1] Chamberlin and Salisbury: *College Geology*, pp. 898-899.

Volcanic Dust Hypothesis. Strange as it seems, volcanic activity may be a contributing cause of glaciation. Volcanic dust from a great explosion is known to remain suspended in the atmosphere for many months. Dust in the atmosphere lowers the temperature of the earth's surface by keeping some of the sun's heat from reaching the earth. During a period of great activity of numerous volcanoes, the earth's surface temperature may be distinctly lowered, and it is perhaps significant that there was widespread, vigorous volcanic activity during the Pleistocene Ice Age.

Conclusion. In conclusion we may say that, as is true of so many other great natural phenomena, no one hypothesis or explanation is sufficient to account for all the features of glacial epochs. Probably several or all, or at least parts of several or all, of the above hypotheses must be properly combined in order to explain the phenomena of glaciation, and hence it is more readily understood why great glacial epochs have not been more common throughout the history of the earth.

CHAPTER XXVI

CENOZOIC LIFE

General Statement

The Cenozoic era is often called the "Age of Mammals" because, for the first time, these most highly organized of all animals became abundant and diversified and were masters of the land.

Taken as a whole, the life of the Cenozoic era was markedly different from that of the Mesozoic. Even in the Tertiary period the most important groups of plants and animals had a decidedly modern aspect. Most of the plants and the invertebrate animals of the Tertiary period belonged to genera which still exist, while the present-day species gradually increased from a small percentage in the Eocene to a large percentage in the Pliocene. Among the vertebrates, the fishes, amphibians, reptiles, and birds differed but little from those of today. The mammals, however, which were small, primitive, and relatively rare throughout the Mesozoic, showed a wonderful development both in number of individuals and diversity of forms. The mammals were, therefore, the most interesting and characteristic organisms of Cenozoic time.

Plants

Vegetation had assumed a rather distinctly modern aspect well before the opening of the Cenozoic era, the great revolution from ancient to modern types having taken place about the middle of the Mesozoic era. During the Cenozoic, however, there was notable progress toward even more modern conditions, so that many genera became the same as now and gradually more and more present-day species were introduced.

Among the simplest or single-celled plants, the *diatoms* deserve special mention. In certain times and places they swarmed in the Tertiary waters. "The microscopic plants which form siliceous shells, called diatoms, make extensive deposits in some places (Fig. 318). One stratum near Richmond, Virginia, is 30 feet thick and is many miles in extent; another, near Monterey, California, is 50 feet thick, and the

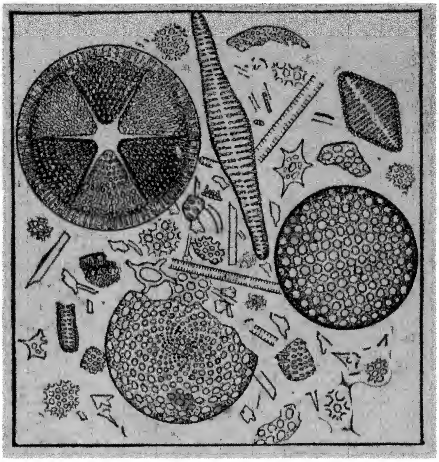


FIG. 318. Diatoms from diatomite of Miocene age at Lompoc, California. Very much enlarged. (After California State Mining Bureau.)

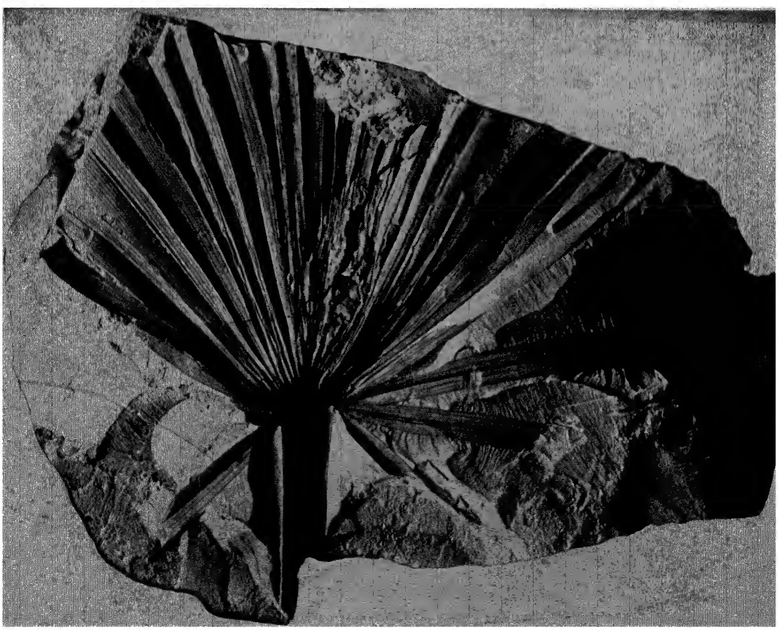


FIG. 319. A well-preserved fossil palm, *Thrimax eocenica,* from the Eocene of Georgia. (After Berry, U. S. Geological Survey, Prof. Paper 84.)

material is as white and fine as chalk, which it resembles in appearance; another, near Bilin in Bohemia, is 14 feet thick. . . . Ehrenberg has calculated that a cubic inch of the fine earthy rock contains about forty-one thousand millions of organisms. Such accumulations of diatoms, (called diatomite, Fig. 237), are made both in fresh waters and salt, and in those of the ocean at all depths."[1]

During the earlier Tertiary, as we have learned, the climate of Europe and the northern United States was warm temperate to even

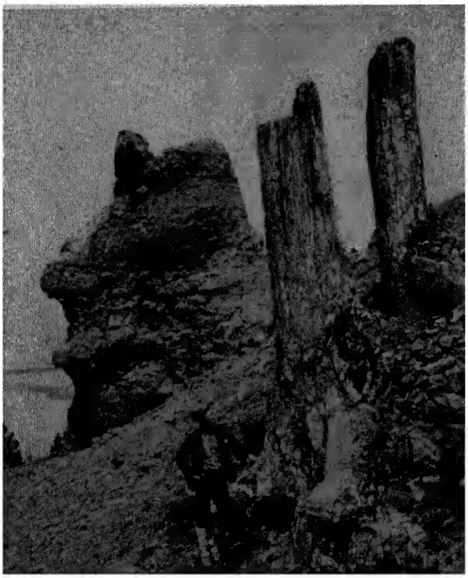


FIG. 320. Two petrified tree stumps in upright position with roots in place. The bold outcrop in the background shows the nature of the volcanic fragmental material in which the trees were buried. Specimen Ridge, Yellowstone National Park. (After F. H. Knowlton, U. S. Geological Survey.)

subtropical and there flourished such trees as *palms* (Fig. 319), *laurels, oaks, willows, chestnuts,* etc., with the addition of *magnolias, figs, poplars, ferns,* etc., in the western interior of the United States and southern Canada. As far north as Greenland and Spitzbergen, there were forests with *maples, camphor trees, figs, laurels, cypresses, poplars,* and *sequoias.* The sequoias, which are of special interest, began in the late Jurassic; attained their culmination in numbers and species in the Tertiary; and are now represented by only two species,—the so-called

[1] J. D. Dana: *Text-book of Geology,* 5th ed., pp. 391-393.

"big trees" and the redwoods,—which are almost wholly confined to California. During the Tertiary they ranged from Greenland on the north to New Zealand on the south, often in great forests.

Many of the present-day forest plants of Central America and northern South America, particularly in the "rain forest" of the Venezuelan Andes, greatly resemble those which lived in western North

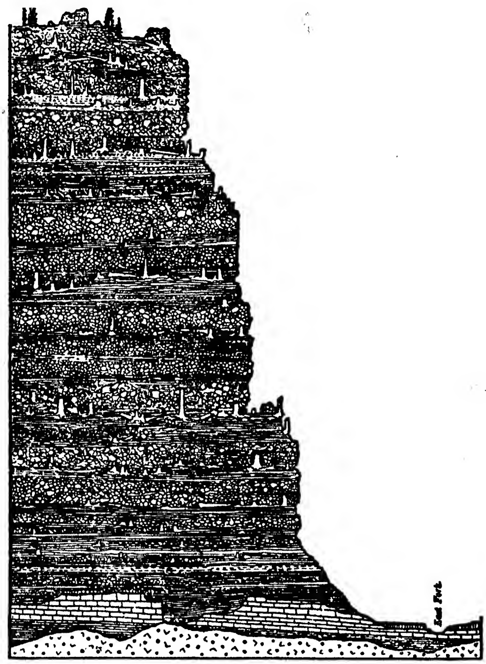


FIG. 321. A diagrammatic section showing a succession of more than a dozen so-called "petrified forests" distributed through a thickness of 2000 feet of volcanic deposits. Specimen Ridge, Yellowstone National Park. (After Holmes, U. S. Geological Survey.)

America during Early and Middle Tertiary times. As the Cenozoic climate gradually became cooler and drier, these plants were driven southward into warmer and moister regions in order to survive. For such a reason, the palms, figs, and magnolias disappeared from the western interior of North America, and the palms from Europe.

Fine examples of Tertiary (Miocene) warmer climate trees, including sycamores, laurels, oaks, pines, and sequoias, are remarkably preserved in petrified form in Yellowstone National Park (Fig. 320). A

dozen or more so-called "petrified forests" occur there at different horizons through a thickness of about 2000 feet of nearly horizontal beds of fragmental volcanic rocks (Fig. 321). Parts of many petrified tree-trunks, with roots in place, are still in upright position where they grew. These are remains of successive forests which were killed and buried by showers of eruptive fragments, then petrified, and since partly exposed by erosion.

In the Tertiary both *grasses* and *cereals* became abundant and they must have had an important influence in the development of the principal groups of herbivorous mammals.

Animals

Since the Tertiary invertebrates were in nearly every way so similar to those of today, we shall give special attention to only a few features of interest.

Among **protozoans,** the *foraminifers* were exceedingly abundant and often remarkable for their great size. Of these the *Nummulites,* so called because coin-shaped, have already been referred to as making up great limestone deposits in the Old World Eocene. They attained a diameter as great as half an inch to an inch (Fig. 322).

Fig. 322. An Eocene foraminifer, *Nummulites.* (From LeConte's "Geology," courtesy of D. Appleton and Company.)

Porifers, cœlenterates, echinoderms, and **molluscoids** were almost wholly modern in character, with crinoids and brachiopods both rare.

Among **mollusks** both *pelecypods* (Figs. 324, 325) and *gastropods* (Fig. 327) were exceedingly common, perhaps more so than ever before, and of very modern aspect (Fig. 326). *Oysters* appear to have reached their culmination in size at least, some having grown to a length of ten to twenty inches and a width of six or eight inches (Fig. 323). Pelecypods are important Tertiary horizon markers (Fig. 325). *Cephalopods,* as we have learned, diminished remarkably at the close of the Cretaceous, the great groups of the *ammonites* and *belemnites* having disappeared, while the *nautiloids* (e.g. Nautilus) were more diversified and wide-spread than now. The *dibranchs* were of the modern squid and cuttle-fish types.

Among **arthropods** all the principal groups except the simplest (e.g. trilobites and eurypterids) were represented, the *crabs* among the *crustaceans* having become numerous and varied. *Insects* are known in

far greater numbers and variety than from any preceding period. All the important groups or orders were represented, including the highest,

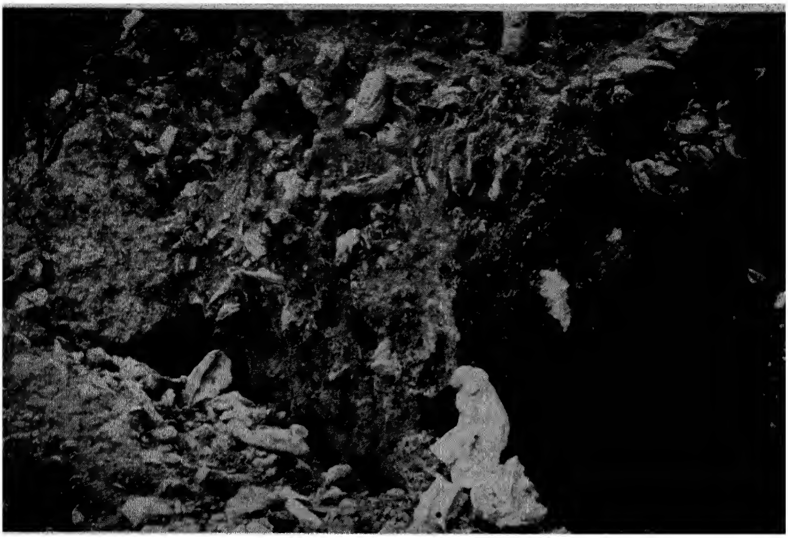
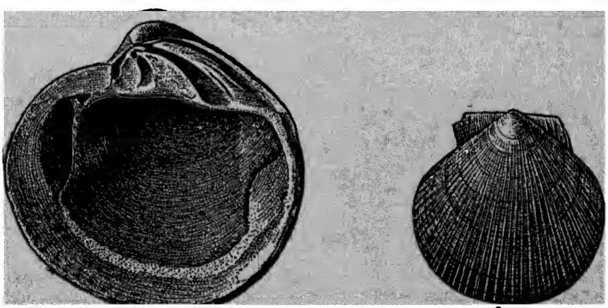


FIG. 323. Large oyster shells, *Ostrea georgiana*, in Eocene strata of Georgia. (After L. W. Stephenson, Geol. Sur. Ga., Bul. 26.)

such as moths, butterflies, beetles, bees, and ants. The prolific vegetation of the period was of course very favorable for insect development.



a b

FIG. 324. Tertiary pelecypods from the North Atlantic Coastal Plain. *a. Venericardia marylandica* (Clark and Martin); *b, Pecten choctanensis* (Aldrich). (After Maryland Geological Survey.)

In a single Miocene stratum a few feet thick at Oeningen, near the Swiss border, more than 900 species of insects have been found. "In

some places the stratum is black with the remains of insects. The same stratum is also full of leaves of dicotyls, of which Heer has described 500 species. Mammalian remains and also fishes are found. . . . Doubtless, at Oeningen, in Miocene times, there was an extensive lake surrounded by dense forests, through which ran a small river emptying

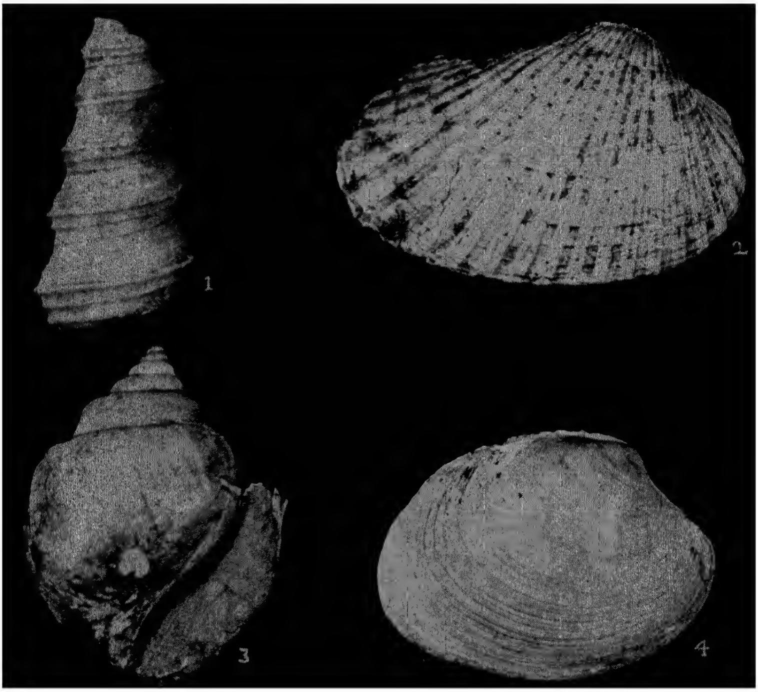


FIG. 325. Pacific Coast Tertiary index-fossil mollusks. *1*, a Miocene gastropod, *Turritella temblorensis* (Wiedey); *2*, a Pliocene pelecypod, *Anadara trilineata*, variety calcarea (Grant and Gale); *3*, an Eocene gastropod, *Pachycrommium inezanum* (Conrad); *4*, an Oligocene pelecypod, *Pitar dalli* (Weaver). All × ⅔. (Photo by C. D. Redmond.)

into the lake; and the insects drowned in its waters, and the leaves strewn by the winds on its surface, were cast ashore by the waves. . . . Over 500 of the Oeningen insects were beetles."[1]

Another remarkable occurrence of fossil insects is in the amber of northern Germany, especially on the shores of the Baltic Sea, where fully 2000 species have been obtained. The amber is a fossil resin of

[1] J. Le Conte: *Elements of Geology*, 5th ed., p. 534.

early Oligocene age derived from certain conifers. The insects were caught in the resin while it was still soft and sticky and they have been perfectly preserved in outline forms (as molds) to the present day in the often quite transparent amber.

At Florissant, Colorado, certain fresh water shales of Miocene age are said to be black with the remains of insects. Over 2000 species are

FIG. 326. Part of a large area covered with Late Tertiary oyster shells which have weathered out of the underlying soft shales or clays. This was an oyster bed in the northern extension of the Gulf of California. Western Imperial Valley, California.

represented as well as various plants, fishes, and even a bird with well-preserved feathers.

Fishes. These were in general much like those of the later Mesozoic, though even more modern in aspect. *Teleosts* (Fig. 328) predominated, but *sharks* were abundant and of great size—60 to 80 feet long—with fossil teeth up to 5 or 6 inches long occurring in immense numbers in some places as, for example, the Gulf Coastal Plain of the United States (Fig. 329).

Amphibians. After their great development in the late Paleozoic, the amphibians never again assumed much importance. In the Cenozoic

they were represented only by such modern types as salamanders, frogs, and toads.

Reptiles. These, too, were quite modern in character, with lizards, snakes, crocodiles, and turtles all common and varied.

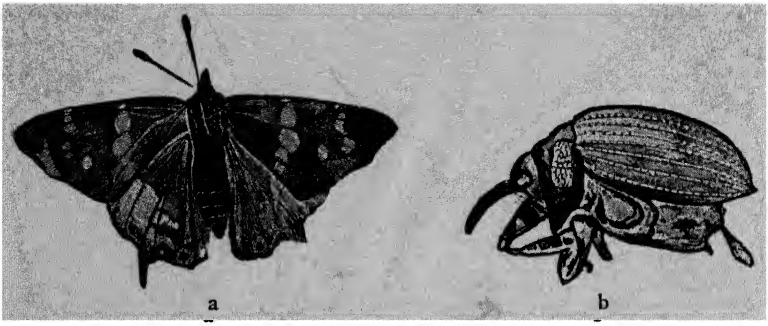


FIG. 327. Insects from the Miocene lake beds at Florissant, Colorado. a, a butterfly, *Prodryas persephone* (Scudder); b, a weevil, *Apion refrenatum* (Scudder).

Birds. These were much more advanced and numerous than in later Mesozoic time, and many of the modern groups had representatives. A few of the more primitive or generalized types, however, still

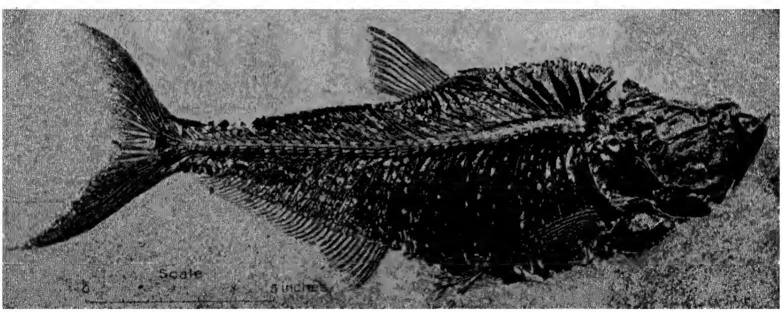


FIG. 328. A nearly perfect fossil teleost fish, *Diplomystus densatus,* from the Eocene of Wyoming. (After Veatch, U. S. Geological Survey, Prof. Paper 56.)

existed in the Early Teritary. Thus a toothed bird has been found in the Eocene of England, though it is to be noted that the teeth were only dentations of the edge of the bill (Fig. 330). With rare excep-

tions, modern birds are entirely toothless. Another special feature was the existence of very large, flightless ostrich-like forms which attained heights up to fully 10 feet. One kind laid eggs more than a foot long.

Mammals (except Primates). *General Statement.* All during the Mesozoic era mammals existed, but they were represented only by comparatively few, small, primitive forms, and they always occupied a very subordinate position in the animal world. They were kept in obscurity by the dominant and diversified reptiles. The mighty crustal disturbance of late Mesozoic time, reaching a grand climax in the Rocky

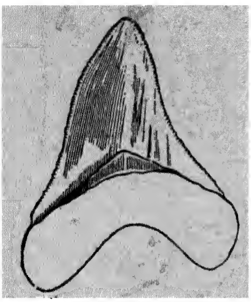


FIG. 329. A shark's tooth from the Eocene of the Gulf Coastal Plain. Length of tooth, 6 in. (After Gibbes.)

FIG. 330. Head of an Eocene bird, *Odontopteryx toliapicus,* showing toothlike projections of the bill. (After Owen.)

Mountain Revolution, left in its wake the end of the reign of reptiles, and the beginning of the rule of the highly organized mammals. Very early in the Tertiary there began a wonderful development of mammals. Evolution of many of the higher groups went on rapidly, so that by the close of the period the mammals had become differentiated into most of the principal modern types. One of the most significant features in the evolution of the mammals during the Cenozoic was the gradual increase in the relative sizes of the brains. The accompanying sketches graphically illustrate this fact (Fig. 331).

With the exception of a few very primitive, Late Cretaceous, insectivorous, placental mammals, only monotremes and marsupials existed during the Mesozoic, but during the Tertiary they were very subordinate to the placentals, and today they are comparatively rare. The Cenozoic was (and is), therefore, very decidedly the "Age of Placental Mammals."

One of the most characteristic features of Pleistocene mammals was the great size of so many. In fact, as regards size and diversity of forms, the mammals may be said to have attained their culmination during the Pleistocene epoch. Comparing the mammals of that epoch with those of today, we find that many species, especially of the large animals, have become extinct, and the world is now (except for man) said to be "zoologically impoverished." The vicissitudes of the climate, i.e. alternations of glacial and interglacial conditions, appear to have "produced a very severe struggle for existence and were fatal to a great many large mammals, causing numerous extinctions over the larger part of the world" (W. B. Scott).

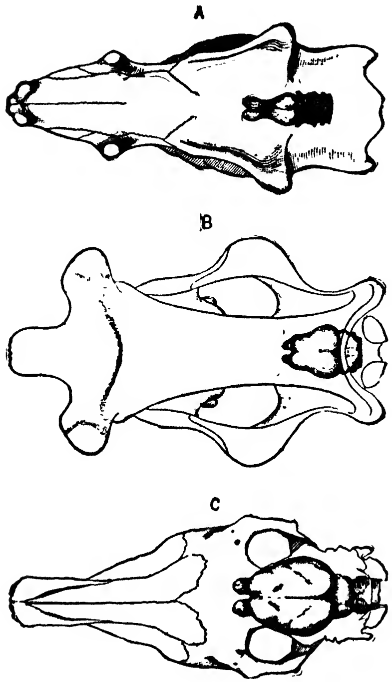


FIG. 331. Sketches to illustrate increase in size of brains of mammals from the Eocene to the present. *A*, Eocene *Uintatherium; B,* Miocene *Brontotherium; C,* modern horse, *Equus.* (After Marsh, from Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company.)

Because of the great wealth of available material concerning Cenozoic mammals, we can do no more, in our brief survey, than to describe some typical examples of the most interesting and better known forms, with emphasis upon evolutionary changes shown by them.

Generalized Mammals of the Eocene. Although mammals were the dominant animals even in the Early Tertiary, nevertheless they were not then differentiated into the more or less clearly defined groups of today such as the *carnivores,* or flesh eaters (e.g. dogs, bears, tigers, etc.); *perissodactyls,* or hoofed mammals with an odd number of toes (e.g. horses, rhinoceroses, etc.); *artiodactyls,* or hoofed mammals with an even number of toes (e.g. camels, deer, pigs, etc.); *proboscidians,* or trunk-bearing hoofed mammals (e.g. elephants); *rodents,* or gnawers (e.g. rats, squirrels, etc.); *insectivores* (e.g. moles, hedgehogs, etc.); *cetaceans,*

or exclusively swimmers (e.g. whales, dolphins, etc.); *primates,* or the very highest of all mammals (e.g. monkeys, man, etc.); and many others. These groups, traced back toward the Early Tertiary, gradually become less and less distinct until, in the Eocene, they cannot be at all distinguished as separate groups, but rather we find ancestral or generalized forms which show combinations of features of the later groups.

FIG. 332. A nearly perfect skeleton of the Eocene *Phenacodus primaevus.* (After Cope.)

One of the most characteristic of these generalized types of the Early Eocene was *Phenacodus* (see Fig. 332). The various species of this genus showed about the same range in size as modern dogs. Each foot had five toes which were supplied with nails rather between true claws

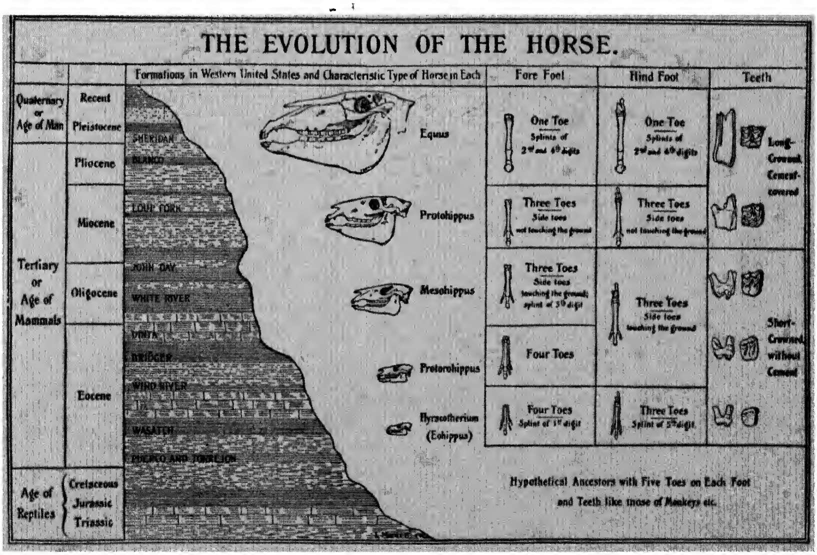


FIG. 333. Chart to illustrate the evolution of the horse family. (After W. D. Matthew, American Museum of Natural History.)

and true hoofs in structure. The simple (primitive) teeth indicate that the animal was omnivorous, that is, both plant and flesh eating. In harmony with other Early Tertiary mammals, the brain was relatively

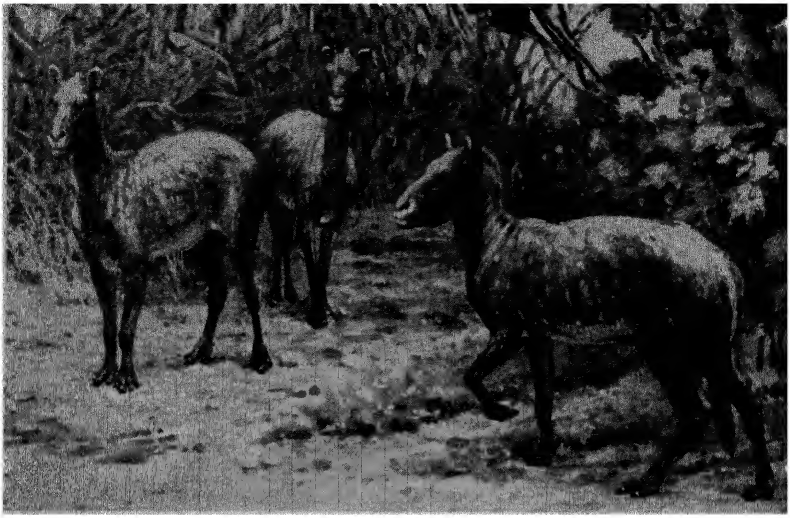


FIG. 334. Primitive or ancestral horses, *Eohippus*, of the Eocene. Restored by C. R. Knight under the direction of H. F. Osborn. (Permission of American Museum of Natural History.)

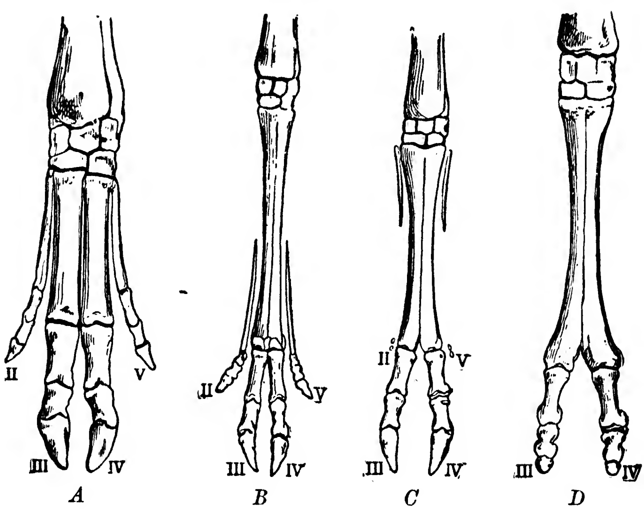


FIG. 335. Evolution of foot of even-toed (artiodactyl) Mammals illustrated by existing forms. *A*, pig; *B*, roebuck; *C*, sheep; *D*, camel. (From Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

small and almost devoid of convolutions, thus pointing to a low grade of mental development.

Perissodactyls (e.g. horse). As an example of the history of the odd-toed, hoofed mammals, we shall consider the well-known evolution of the *horse* family. At least forty species of this family, ranging from Early Eocene to the present, have been described, and practically every connecting link in the evolution of the family is known. Only a few of the most important changes can be noted in our brief description, which

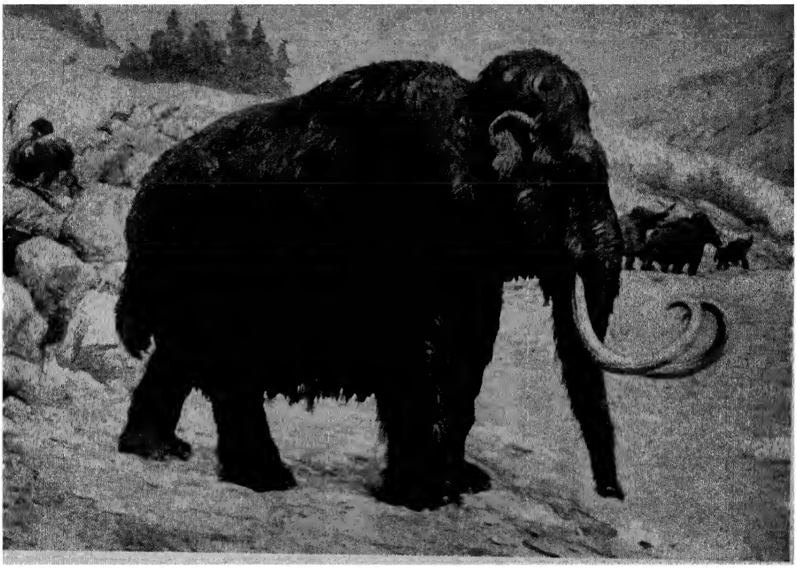


FIG. 336. A mammoth elephant, *Elephas primigenius,* restored by C. R. Knight. (Permission of American Museum of Natural History.)

is, in fact, not much more than an explanation of the excellent chart shown in Fig. 333. The earliest form, called *Eohippus,* occurring in the lower Eocene, was about the size of a large cat (Fig. 334). On the forefoot it had four functional toes (one larger than the others) and a splint or imperfectly developed fifth toe. The hind foot had three functional toes and a splint. Doubtless this early member of the horse family was derived from an original five-toed ancestor whose general structure was something like Phenacodus. In the later Eocene *Protorohippus* had four distinct toes on the front foot and three on the hind foot, but with no sign of splints. This form was but little larger than Eohippus. During the Oligocene *Mesohippus* had three functional toes

(the middle one being distinctly larger), with the former fourth toe reduced to a splint on the front foot, while the three functional toes

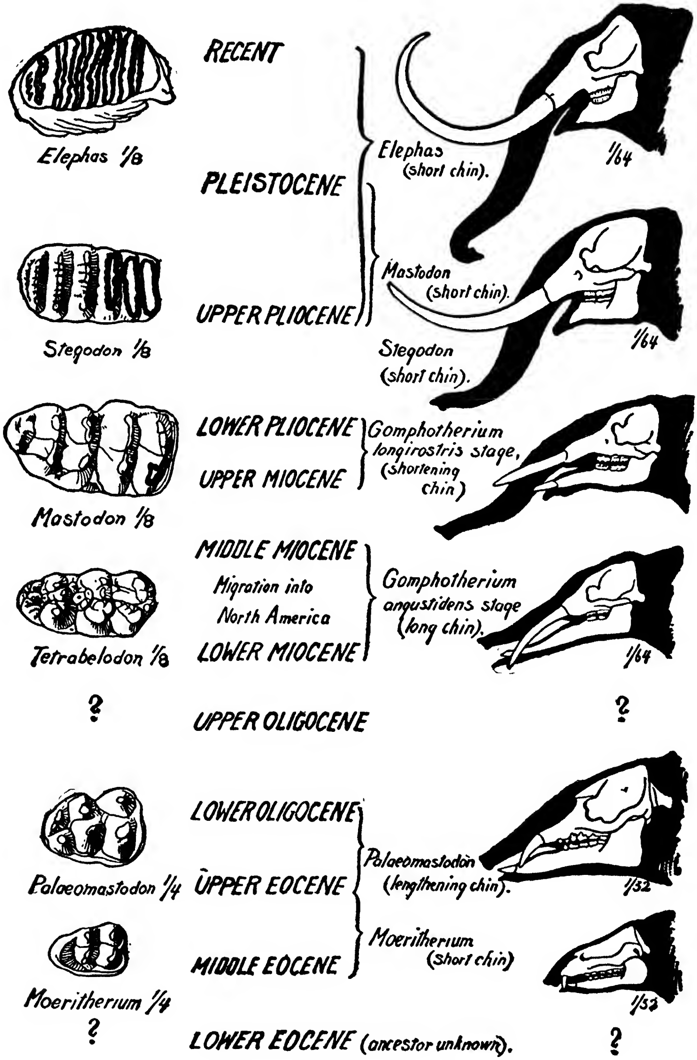


FIG. 337. Chart to illustrate the evolution of the elephants. (From Scott, after Lull, modified by Sinclair, by courtesy of The Macmillan Company.)

continued on the hind foot. It was about the size of a sheep. In the Miocene *Protohippus* had three toes on both fore and hind feet, but in

each case only one was large and functional, with the other two small toes not long enough to reach the ground. This form was about the size of a pony. During the Pliocene and Quaternary, *Equus,* or the modern horse, had, and has, one toe only on each front and hind foot with the two side toes of Protohippus reduced to mere splint bones, entirely non-functional. Thus we see that the middle toe of the original five-toed ancestor has developed, to the exclusion of the others, and it is thought that this has tended toward greater fleetness of foot. While these evolutionary changes took place, there were also gradually developed longer and more complex teeth; the two entirely separate bones (radius and ulna) of the fore limb gradually became consolidated into a single strong bone; and the brain steadily increased in relative size.

Artiodactyls (e.g. camel). These even-toed, hoofed mammals (Fig. 335), like the odd-toed ones, were descended from a five-toed Eocene ancestor. In their development the first toe disappeared, while the middle pair of the remaining four became larger and the two side toes became smaller and smaller, having disappeared altogether in such a type as the modern camel. This sort of evolution in the camel family has been traced in almost as much detail as in the horse family. Beside the camel, other two-toed existing forms are deer, cattle, and sheep. The two-toed artiodactyls now predominate, while the four-toed forms (at present represented e.g. by hogs and hippopotami) culminated in the Tertiary.

Proboscidians (e.g. elephant). This group of hoofed mammals, characterized by the proboscis (trunk), has been traced through many intermediate forms back to primitive Eocene ancestry. Proboscidians culminated in the Pliocene, when they were the largest (up to 13 or 14 feet high), the most numerous, and widespread over much of the earth except Australia. *Mastodons,* now wholly extinct, are characterized by having knoblike prominences on the chewing surfaces of their large teeth (Fig. 338a), while the true *elephants* (including the extinct *Mammoths*) have large nearly flat grinding surfaces on their teeth (Fig. 338b). True elephants also nearly always show greater curvature of the tusks. The mammoth had long brown hair (Fig. 336).

FIG. 338. *a,* mastodon tooth; *b,* mammoth tooth. Both viewed from the side.

The accompanying sketches (Fig. 337), together with the following excellent summary by Lull, will give a good idea of the evolution of the proboscidians. "Increase in size and in the development of pillar-like limbs to support the enormous weight. Increase in size and complexity of the teeth and their consequent diminution in numbers and the development of the peculiar method of tooth succession. The loss of the canines and of all of the incisor teeth except the second pair in the upper and lower jaws and the development of these as tusks. The gradual elongation of the symphysis or union of the lower jaws to strengthen and support the lower tusks while digging, culminating in *Tetrabeledon* (or *Gomphotherium*) *angustidens*. The apparently sudden shortening of this symphysis following the loss of the lower tusks and the compensating increase in size and the change in curvature of those of the upper jaw.

"The increase in bulk and height, together with the shortening of the neck necessitated by the increasing weight of the head with its great battery of tusks, necessitated the development of a prehensile upper lip which gradually evolved into a proboscis for food gathering. The elongation of the lower jaws implies a similar elongation of this proboscis in order that the latter may reach beyond the tusks. The trunk did not, however, reach maximum utility until the shortening jaw, removing the support from beneath, left it pendant, as in the living elephant."

During Quaternary time the *proboscidians* were well represented by both the *mastodons* and the *mammoths*. These were smaller than those of the Late Tertiary or about the size of modern elephants. "During Pleistocene times the Proboscidia covered all of the great land masses except Australia, but were diminishing in numbers, and toward the close of the Pleistocene the period of decadence began, resulting in the extinction of all but the Indian and African elephants of today" (Lull). The mastodon roamed only over much of North America and part of South America, having become extinct in the Old World in the Late Tertiary. The mammoth had a much wider range from the Atlantic states to Alaska; across Siberia; through central Europe; and even to the British Isles. Fine examples of the almost perfect preservation of entire organisms of now extinct forms are furnished by specimens of frozen mammoths which have been in nature's "cold storage" for thousands of years in the gravels or ice of Siberia. In several cases much of the hide, long brown hair, and even the flesh are known to have been perfectly preserved, the flesh having been eaten by dogs or even the

natives themselves. Two of the finest specimens were discovered in 1806 and 1901.

Carnivores (tigers, dogs, etc.). These modern flesh-eaters can be traced back to a generalized order or group (so-called *creodonts*, Fig. 339) which had certain characters suggesting the insect-eaters, hoofed mammals, and marsupials, as well as the carnivores. These creodonts or ancestral flesh-eaters had small, simple brains and many small teeth. In the course of evolution the existing carnivorous families have been derived from them.

Rodents (rats, porcupines, squirrels, etc.). The rodents (gnawers) can be traced back to the Early Eocene, when the incisor teeth were just

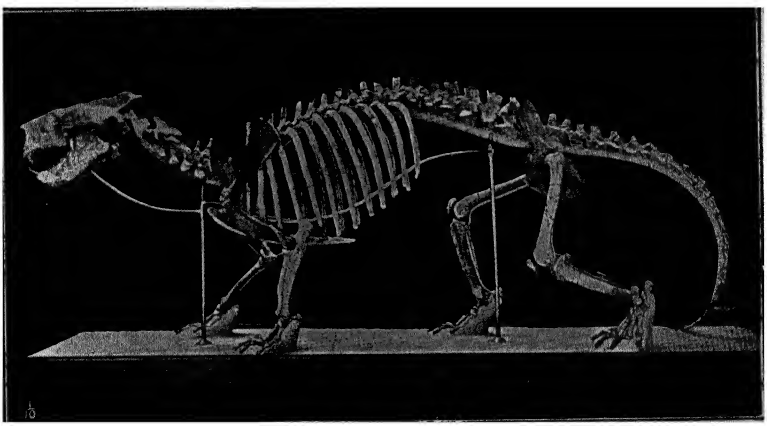


FIG. 339. Skeleton of an Eocene creodont, *Patriofelis*. (After Osborn, from Chamberlin and Salisbury's "Geology," courtesy of Henry Holt and Company.)

developing a structure suitable for gnawing. By the middle of the Eocene the rodents were common and their incisors were highly specialized for gnawing. Primitive squirrel-like forms are known from the Late Eocene. Certain Pleistocene rodents were 5 feet long.

Insectivores (e.g. moles, hedgehogs, etc.). These have also been traced back to the Eocene, and, like the rodents, they still show many of their ancestral or primitive features. They have changed much less than most of the other classes of mammals.

Among the *edentates* (sloths, armadillos, etc.), which belong to the simplest placental mammals, the *Megatherium* and the *glyptodonts* are of special interest. The former (see Fig. 340), a sort of giant ground-

sloth, was remarkably massive and attained a length of 15 to 18 feet. Its thigh bones were two or three times the thickness of those of the elephant, and its front feet were about a yard long. The tooth structure shows it to have been a plant feeder. This powerful creature could easily have toppled over small trees in order to strip off the leaves. The glyptodonts (see Fig. 341) were giant armadillos up to 8 feet long and armed with a very strong turtle-like carapace. These edentates,

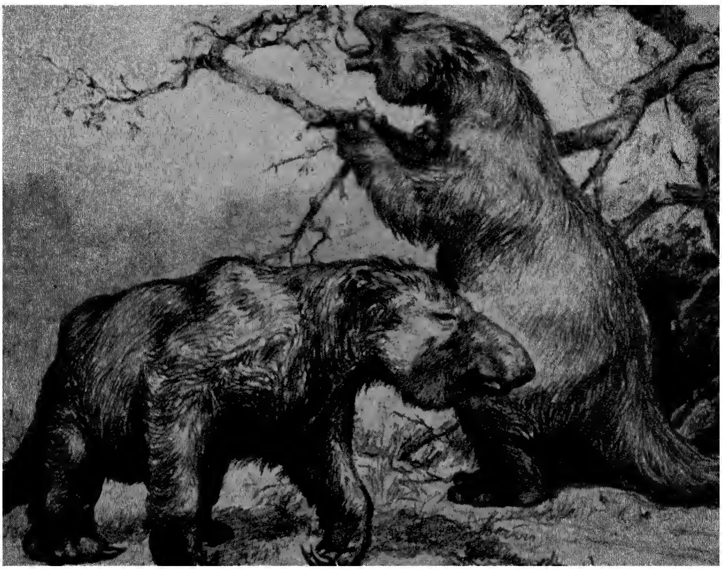


FIG. 340. A great ground-sloth, *Megatherium americanum*. (After W. B. Scott, by permission of The Macmillan Company.)

including many species, were common in South America and in North America as far north as Pennsylvania and Oregon.

Cetaceans (e.g. whales, porpoises, etc.). In our study of Mesozoic reptiles we found that certain forms took to the sea and became marine fishlike creatures, such as the ichthyosaur and the mosasaur. So in the Tertiary (even in the Eocene) certain mammals became so adapted to the water environment as to become fishlike forms, such as whales, porpoises, etc., which are often popularly regarded as true fishes. Apparently we have here an example of retrogression in evolution, because true land animals took to the water and their legs degenerated into swimming paddles. Certain whalelike forms (zeuglodons) of the Eocene

reached lengths up to 60 or 80 feet and must have been extremely abundant, their vertebræ often being found in great numbers in Alabama and other places.

Pleistocene Bones in Asphalt. Fossil bones in a wonderful state of preservation, occurring under unique conditions, have been found in great numbers in the so-called La Brea tar and asphalt deposits in Los Angeles. The tar and asphalt are oxidized petroleum which has been

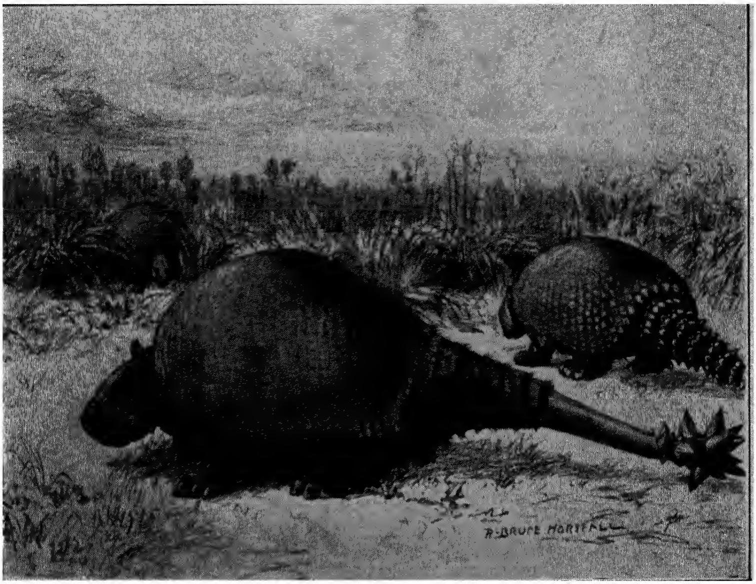


FIG. 341. Great armored glyptodonts, *Doedicurus clavicaudatus* and *Glyptodon clavipes.* (After W. B. Scott, by permission of The Macmillan Company.)

oozing upward to the surface along a fracture in the earth's crust since Middle Pleistocene time. The animals lost their lives by becoming trapped in the tar pits. Among the many kinds of now extinct animals represented in fossil condition are great *elephants, saber-toothed tigers, giant ground-sloths, bisons,* and *birds* (Fig. 342).

Distribution of Quaternary Plants and Animals. *Effects of Glaciation.* The alternations of glacial and interglacial climates caused corresponding migrations of colder and warmer climate animals and plants. While a great ice sheet was advancing, Arctic animals and plants ranged farther and farther southward even into what are now temperate latitudes. Thus the *musk ox* ranged southward to Iowa and

Kentucky, and the *walrus* to Virginia, while in Europe the *reindeer, Arctic fox,* etc., ranged southward into France. During the retreat of a great ice sheet, the Arctic fauna and flora retreated to colder climatic conditions, either by following the ice front northward or by going up the mountains as they were freed from the ice. This retreat up the mountains affords a ready explanation of the fact that certain Arctic plants and animals (especially insects) are now found, in the Alps and higher parts of the White Mountains of New Hampshire, separated

FIG. 342. Bones of various Pleistocene mammals exposed by excavation in an asphalt deposit. Among them are, *1,* bison pelvis; *2,* saber-toothed tiger skull; *3,* American lion femur; *4,* giant ground-sloth femur; *5,* dire wolf skull; and *6,* Pacific horse skull. The asphalt is oxidized mineral tar. Note the fresh tar running down the right side. La Brea tar pits, Los Angeles, California. (Photo by the Los Angeles Museum, by courtesy of H. R. Hill.)

from their former habitat by many hundreds of miles of climate now too mild for them to cross.

Effects of Diastrophism. During the Pleistocene, the geographical environment favored a very widespread distribution of mammals over most of the land areas. Thus North America and South America were connected; North America and Asia were joined across what is now the Bering Sea; and Eurasia and Africa were well connected. Australia was, and had been for a long time, one of the largest isolated land masses, and herein lies the explanation of its most peculiar fauna and

flora. For example, of the many known species of mammals all are non-placentals, that is, they are monotremes and marsupials. Non-placentals inhabited most of the great land areas (including Australia) during the Mesozoic era. Since true placental mammals made their appearance in the Early Tertiary, it is quite certain that Australia was isolated from the Asiatic continent before the Tertiary and that under the more local conditions and less severe struggle, placentals were never evolved there and they never got there from other continents, except as artificially introduced by man in Late Quaternary time.

Madagascar also has a mammalian fauna very peculiar to itself. This island was separated from the mainland before Quaternary time, and its mammals, because of less severe struggle for existence, have changed

FIG. 343. A lemur from Madagascar. It is a living representative of the very primitive Eocene primates. (After Beddard.)

more slowly and in their own way as compared with those of the African continent.

The coast islands of southern California show similar relation to the mainland, but more especially as regards the plant species.

Primates (except Man). The *primates* comprise the highest and most complex group of all animals. There are two main divisions—the *lemuroids*, including *lemurs* and *tarsius;* and the *anthropoids*, including monkeys, apes, and man. Primates are comparatively uncommon in fossil form because they were never numerous like many other animals, and because they were land animals, usually living in trees. Conditions for their fossilization were, therefore, seldom favorable. During the last 75 years, however, so many fossil primates have been found that we are now able to outline the main steps in the general evolution of the primates (including man) from the Early Eocene to the present.

The oldest known true primates—the lemuroids—date from the Eocene, and they represented the lowest stage or type of all known primates. Both the lemurs, with descendants now living in Madagas-

car, and the Tarsius, with present-day descendants in the East Indies, existed in the Eocene.

From Oligocene strata we have records of the most primitive anthropoids or anthropoid-like primates, including both primitive or ancestral monkeys and apelike creatures.

Many species of true anthropoids (both monkeys and apes) existed during both the Miocene and Pliocene epochs, as proved by the fossils found in widely separated parts of the world. Various species have of course ranged to the present time.

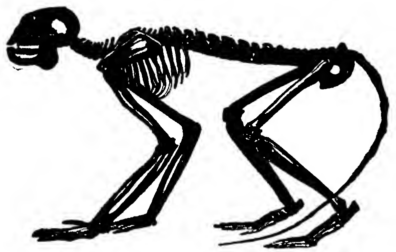


FIG. 344. One of the early monkeys, *Mesopithecus pentelici*, from the Miocene of Europe, restored by Gaudry. Length of specimen, about 20 inches.

Geologic History of Man. *General Statement.* Thus far we have said little about the interesting and important subject of man's first appearance, and nothing about his early history. Since man, who represents the very highest type of organism which has ever inhabited the earth, belongs to one of the most recent and important groups of animals, it is appropriate that a brief discussion of his origin and early history be reserved for the very last. Up to the present, at least, progressive organic evolution through hundreds of millions of years has reached its climax in man.

Because of additional discoveries and better methods of study, our knowledge of prehistoric man is becoming more satisfactory year by year. The ablest students of the subject have agreed upon several important points, while regarding others there is still much disagreement. There is quite a general agreement (1) that man has evolved from lower forms of primates; (2) that there are clearly recognizable at least two types or species of true man, namely, (a) *primitive man* (Middle and late Middle Pleistocene), now extinct, and (b) *Homo sapiens* (Late Quaternary), represented by existing man; (3) that true man certainly existed during the Pleistocene; (4) that, on a most conservative basis, true man was on the earth no less than 200,000 years ago; and (5) that there is no positive evidence for the existence of true man earlier than the Early Pleistocene or Glacial epoch.

Differences of opinion commonly surround such as: (1) The classification of the early ancestral forms, that is whether they should be called

apes, manlike apes, or apelike men;[1] and (2) the portions of the Quaternary system represented by the deposits in which man's bones or implements are found, or by the remains of animals found associated with man's bones or implements.

Bones and implements of ancient man, and his early ancestral forms, are found chiefly in river gravels, loess, caves, and interglacial deposits.

The following tabular arrangement is introduced in order to graphically represent (synoptically) certain of the most significant features in connection with the geologic history of man. It should be clearly borne in mind that, in some respects, these are only tentative arrangements, though they do summarize our most recent knowledge based upon the work of able students of the subject.

CHRONOLOGICAL TABLE OF MAN AND HIS ANCESTORS

Geologic Age		*Estimated Time Ago*	*Cultural Age*			*Fossil Forms*	
Post-Glacial or Recent epoch			Historic age		Iron and bronze work	Homo sapiens	Modern
			Neolithic age		Well-shaped and polished stone implements	Homo sapiens	Modern
Pleistocene or Glacial epoch	Fourth glacial stage	20,000 years	Paleolithic age	Magdalenian Solutrean Aurignacian	More or less well-formed stone implements	Homo sapiens	Crô-Magnon
	Third interglacial stage	150,000 years	Paleolithic age	Mousterian	More or less well-formed stone implements	Primitive man	Neanderthal race
	Third glacial stage		Paleolithic age	Acheulian	More or less well-formed stone implements	Primitive man	
	Second interglacial stage	500,000 years	Paleolithic age	Chellean	More or less well-formed stone implements	Primitive man	
	Second glacial stage		Paleolithic age	Pre-Chellean	Very rough stone implements	Ape man	Piltdown
	First interglacial stage	750,000 years	Paleolithic age	Pre-Chellean	Very rough stone implements	Ape man	Peking Heidelberg
	First glacial stage		Paleolithic age	Pre-Chellean	Very rough stone implements	Ape man	Java Australopithecus
Pliocene epoch		1,000,000 years	Eolithic				Apes

Ape Man. Among the most ancient known remains of man's early ancestral forms (ape men), five of special interest and importance will be described. These are all of greater antiquity (Early Pleistocene) than any bones of what are considered to be true human beings. It should, however, be emphasized that there is no sharp line of demarcation between fossil manlike apes and man, but rather there are transitional or gradational forms.

Australopithecus, or the so-called "southern ape," lived in South Africa. A skull and jaw bones were found in 1925 buried in a cave

[1] It is important to note that this very difference of opinion is one of the strongest arguments in favor of the organic evolution of man, because practically all intermediate types between true man and certain higher primate forms are known.

deposit with remains of extinct animals of Early Pleistocene age. He was an ape, but more advanced than any living ape. He was a very old, low type of the manlike apes or ape men (Fig. 345).

Pithecanthropus erectus, also known as the "Java man," was discovered in 1891. Parts of a skull and lower jaw, several teeth, and a thigh bone, indicating erect posture, were found under considerable sediment. Other skulls were found during 1936-39. Associated with the remains were bones of extinct animals of Early Pleistocene age. The low, thick skull cap is plainly apelike with narrow, low forehead, and very massive, prominent brow ridges. The teeth were of rather human struc-

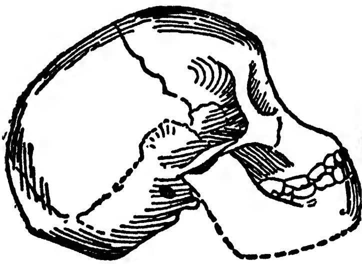


FIG. 345. The skull of *Australopithecus,* or the "southern ape." (After Broom.)

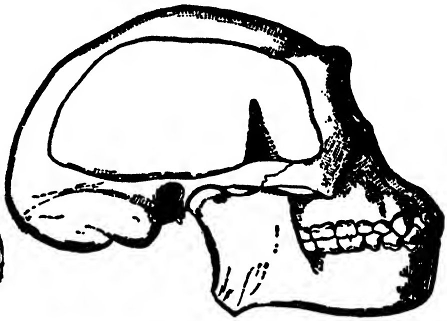


FIG. 346. Restoration of the skull of *Pithecanthropus erectus.* (After Du Bois, from Norton's "Elements of Geology," by permission of Ginn and Company, Publishers.)

ture, but they projected strongly in front. The creature had a protruding mouth and practically no chin, as in the apes. The size of the brain (750-900 c.c.) was much less than that of lower forms of true man. Pithecanthropus represented an old, low type of the manlike apes (Figs. 346, 347).

Sinanthropus pekingensis, often called "Peking man," was discovered in 1928-29 near Peiping, China. Many skulls, jaws, and some limb bones have since been found buried in a cave deposit. The low, thick-boned skull shows a low, receding forehead, receding chin, massive brow ridges, and a wide, comparatively flat nose. The brain size (1000 to 1200 c.c.) was intermediate between Pithecanthropus and lower forms of true man. Both brain pattern and teeth have human affinities. The limb bones show that he stood erect. Charcoal buried with the bones prove that Sinanthropus knew the use of fire. Various associated bones of extinct animals and many crude stone implements show that he lived fully 500,000 years ago.

Paleoanthropus heidelbergensis, or so-called "Heidelberg man," is represented only by a well preserved jaw with teeth. It was buried under 70 feet of sediment near Heidelberg, Germany. The jaw is very massive (apelike) with practically no chin, but the teeth are of human structure. It is definitely of Early Pleistocene (first interglacial) age as shown by directly associated bones of other animals of that age.

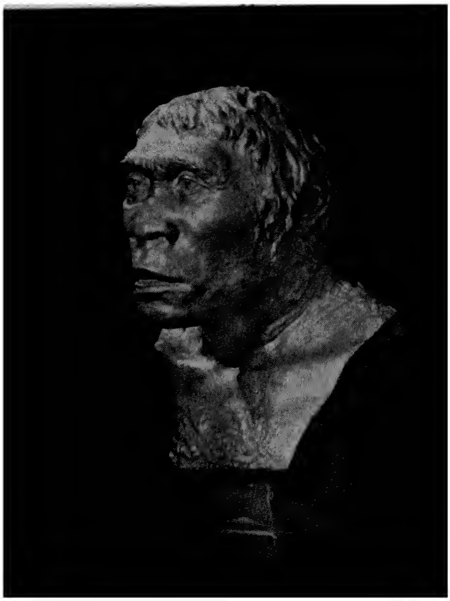


FIG. 347. A restoration of the head of *Pithecanthropus erectus.* (After J. H. McGregor, courtesy of the American Museum of Natural History.)

Eoanthropus dawsoni, or "Piltdown man," is represented by most of a skull and teeth found during 1911-12 and 1917 at Piltdown, England. The remains were accompanied by crude flint implements (pre-Chellean) and bones of extinct animals of rather Early Pleistocene age. The strong protruding jaw and teeth, the absence of a real chin, and the unusually thick skull cap are strongly apelike. Eoanthropus had a brain as large as that of true man, but it was somewhat flatter. It was, therefore, exceptionally large for such an ancient creature. Eoanthropus had an ape jaw and a human brain. He represented a distinctly human type of the ape men. Associated charcoal and burnt implements prove that he used fire.

Summarizing the characteristics of the ape men, it is clear that these creatures, which lived more than half a million years ago, were definitely, though variably, intermediate between true or typical apes and lower forms of true or typical human beings. Some of them quite certainly

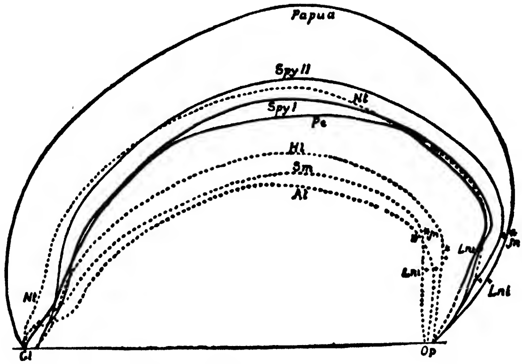


FIG. 348. Comparison of skull profiles of lowest types of man and highest apes. Papuan, modern native of New Guinea; *Spy 1* and *2*, men of *Spy; Nt,* Neanderthal man; *Pe, Pithecanthropus erectus; Hl,* a gibbon; *At,* a modern chimpanzee. (By Marsh after Du Bois, from Le Conte's "Geology," courtesy of D. Appleton and Company.)

walked erect, but with an ape carriage. Their Early Quaternary age is proved either by association of their fossil remains with bones of animals of that age, or crude (Early Paleolithic) stone implements, or both. Most of them had comparatively small flattened brain cases, receding fore-

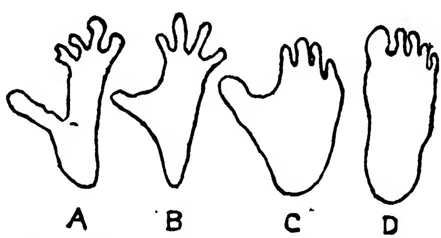


FIG. 349. A comparison of feet of primates. *A,* lemur; *B,* monkey; *C,* ape; and *D,* man.

heads, powerful jaws, massive continuous brow ridges, projecting teeth, and strongly receding chins. Eoanthropus, combining a definitely human brain and moderate brow ridges with other definitely ape features, was the most exceptional. Possibly he was a real ancestor of modern man.

In regard to the manlike apes in general A. S. Woodward says that the facts "are enough to show that, in the beginning, the human skull was much more varied than it is at the present day. There were, indeed, several distinct approaches to modern man before his type became

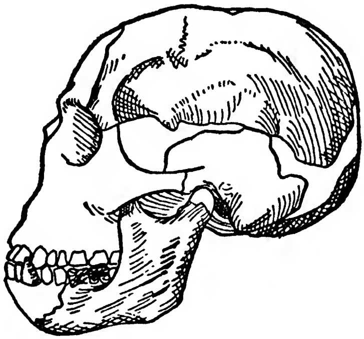


FIG. 350. Restoration of the skull of *Eoanthropus dawsoni*, or "Piltdown man." The unshaded parts are filled in. (After Hunter.)

fixed and persistent, just as there were parallel lines of evolution, effective and non-effective, in the ancestry of other modern mammals." That all of the examples of ape men of Early Pleistocene age above described were closely related in the primate world of that time is strongly sug-

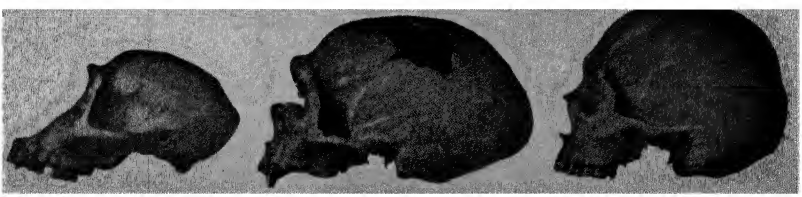


FIG. 351. Comparison of skulls; *a*, modern chimpanzee; *b*, Neanderthal man; *c*, modern Frenchman. (After E. Rivet, from New York State Museum Bulletin 173.)

gested by the skull of Sinanthropus which exhibits a striking combination of the special features of the others.

Primitive Man. The oldest form of primate which, by rather common agreement, is considered to have represented true man appeared in about the middle of the Pleistocene epoch. Many examples of implements and bones of Middle and late Middle Pleistocene (or primitive) man have been found in various parts of the Old World. It is often

difficult to be sure of the precise glacial or interglacial stage to which given specimens belong. Their geologic age is, however, proved by the conditions under which they have been found. Thus the bones or implements have often been found buried at considerable depths in cave

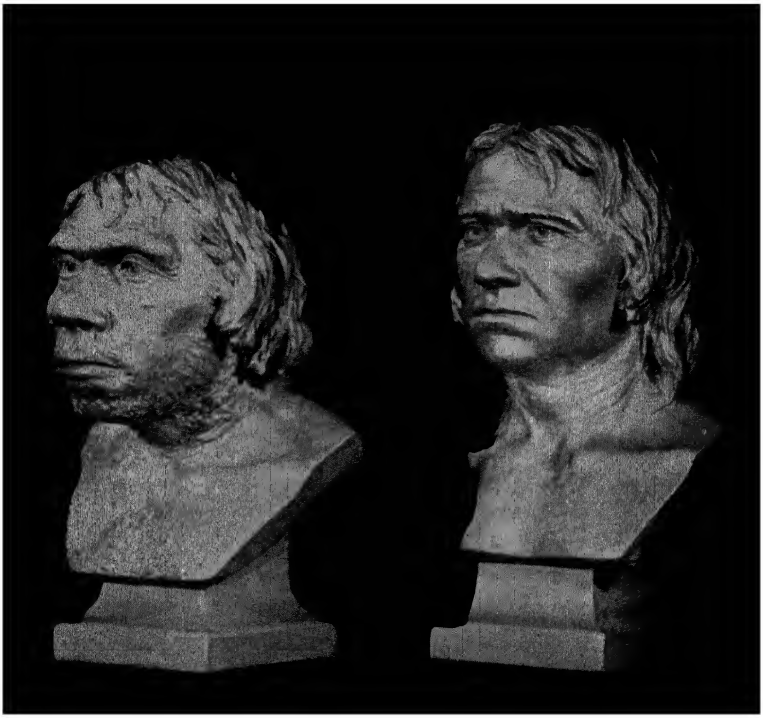


FIG. 352. Heads of Neanderthal man (left) and Crô-Magnon man (right) restored. (After J. H. McGregor, courtesy of the American Museum of Natural History.)

deposits or in sediments which have not been disturbed since their deposition, or in direct association with the remains of contemporaneous Pleistocene animals such as the mammoth, cave bear, cave hyena, woolly rhinoceros, reindeer, musk ox, bison, and horse.

The fairly well-shaped stone implements, including hand axes, flint-tipped spears, and scrapers, indicate the Chellean, Acheulian, and Mousterian cultural ages. That primitive man hunted the wild beasts of

his time is proved by the direct and frequent association of his bones and hunting weapons with the bones of contemporary animals.

FIG. 353. A restoration of Paleolithic Neanderthal Man. (Copyright by Field Museum of Natural History, and used by permission.)

It is convenient to group together the more typical examples of Middle and late Middle Paleolithic man under the term *"Primitive man"* as distinguished from Homo sapiens whose representatives made

their first appearance in Late Paleolithic (or Late Pleistocene) time. Examples of living approaches to primitive man are the native papuan of New Guinea and the bushman of Australia. The native Tasmanian, who became extinct during the nineteenth century, was even more like Middle Paleolithic primitive man.

Middle Paleolithic man is known almost entirely from the numerous crude stone implements (Fig. 354), particularly hand axes and hide

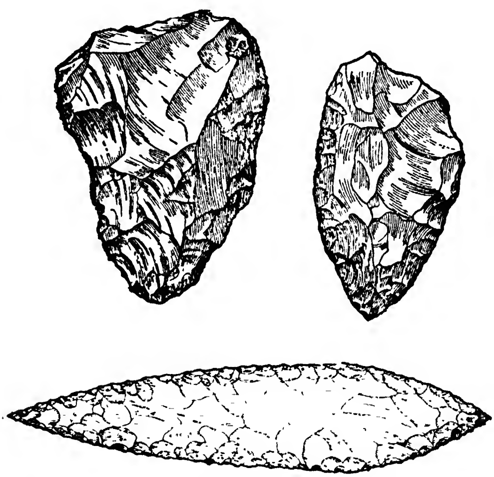


Fig. 354. Sketches of stone implements of various cultural ages used by Paleolithic man. Upper left, Chellean; upper right, Mousterian; and lower, Solutrean. (From "The Nature of the World and Man," by permission of the University of Chicago Press.)

scrapers, which he left, but actual bones positively known to be of this age are as yet unknown. The implements represent the Chellean and Acheulian cultural ages.

Late Middle Paleolithic man lived during the Mousterian cultural age. He is well represented not only by numerous implements from many localities, but also by bones and practically complete skeletons, in many places. His implements were generally better made (Fig. 354) and used for more purposes than those of Early Paleolithic man. Associated ashes, charcoal, and burnt bones, prove that he knew the use of fire.

Late Middle Paleolithic man is typified by the Neanderthal race, so named because of the skeletons found (1856) in the Neander Valley, Germany. Neanderthal men "were short, bull-necked, barrel-chested individuals, with many features of the bones of the trunk and of the

extremities suggesting an affinity with the great apes less remote than that of modern man. The most striking features were, however, those of the skull. The long and narrow brain cases were of moderate size or even large, but flattened down and low; their orbits were sur-

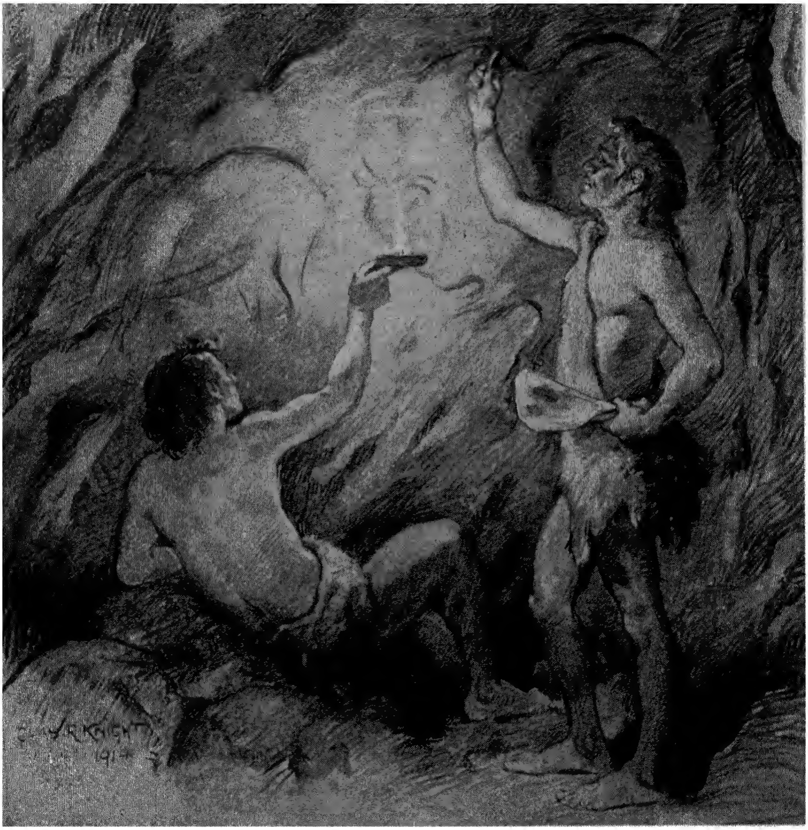


FIG. 355. Restoration of Late Paleolithic (Crô-Magnon) men decorating a cave. (After C. R. Knight, courtesy of the American Museum of Natural History.)

mounted with huge bony brow ridges, behind which the forehead retreated in an ignominious fashion. The jaws were protrusive to the verge of snoutiness; the chin receded practically to a vanishing point; and the teeth were massive, but without canine projection" (E. A. Hooton). Neanderthal man (Fig. 353) walked with stooping shoulders, and his neck and head were carried forward in the same curvature

as the back, so that the head hung forward on the chest. His hands and feet were large and his knees bent. His skull was comparatively thick. Neanderthal man "is genealogically the latest to retain several specially apelike characters associated in a single individual" (A. S. Woodward).

In addition to the skeletons found in the Neander Valley, brief mention will be made of a few others. In a cave at Spy, Belgium, two nearly complete skeletons of Neanderthal man have been found. They were associated with remains of contemporaneous Pleistocene animals. In

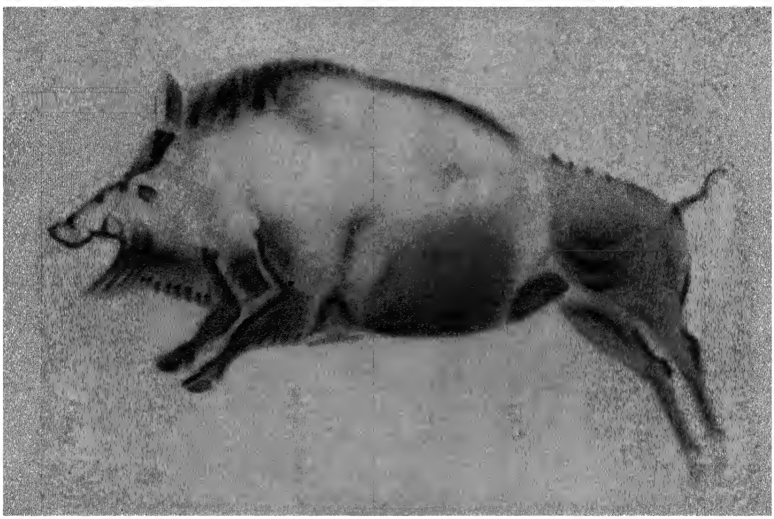


FIG. 356. A charging wild boar, one of the best paintings by Late Paleolithic man in the cave at Altamira, Spain. (After Cartailhac and Breuil, courtesy of the American Museum of Natural History.)

the Perigord district of southwestern France, there are several caves in which were found relics of man believed to range from Middle to Late Paleolithic time. An important discovery (1908) was in a cave at La Chapelle-aux-Saints in southern France. The remains are a nearly perfectly preserved skull together with the lower jaw and many bones of the body. Among the associated animal remains were the reindeer, horse, rhinoceros, ibex, wolf, badger, and boar. This La Chapelle specimen seems to represent a fine typical example of late Middle Paleolithic, or Neanderthal, man. Near Krapina in Croatia hundreds of human bones, associated with thousands of bones of other animals, were

found in 1899 in a rock shelter. "The skulls are of men, women, and children, and are slightly broader than the later (Neanderthal) ones, with less prominent eyebrow ridges and not quite such massive jaws, but there is the same retreating chin and flat crown" (E. W. Berry). A number of Neanderthal skeletons have recently been found at the base of Mount Carmel and near Galilee in Palestine; Crimea; and Rhodesia. Mousterian stone implements, without associated human bones, have been discovered in many parts of western Europe, Asia Minor, and North Africa.

The Neanderthal race existed for scores of thousands of years through the third and last interglacial stage, and ranged over large parts of western and southern Europe, western Asia, and central and northern Africa.

Homo sapiens. Late Paleolithic man lived during the Aurignacian, Solutrean, and Magdalenian cultural ages of Late Pleistocene time, that is during the fourth glacial stage. He is typified by the Crô-Magnon race which seems to have invaded Europe, probably driving out Neanderthal man. His stone and bone workmanship was the finest of Paleolithic time (Fig. 354), and he has left records of drawings and pictures in caves.

Crô-Magnon man is classed with modern man as *Homo sapiens.* He was longer in arms, legs, and head than modern man. The average size of his head was fully as great as that of present-day man, but somewhat less than that of the highest types of the latter. Both skull and forehead were high, but his cheek bones were unusually wide, causing him to have a broad face. He had a well-formed chin. His brow ridges were fairly heavy. He stood taller and straighter than Neanderthal man.

Numerous skeletons of Crô-Magnon man have been found in various parts of Europe. These are usually associated with many bone and stone implements, and with bones of various animals, especially horses. Some of the best finds have been made in or near Aurignac, Solutré, Grimaldi, and Dordogne Valley in France, and at Předmost in Czechoslovakia. The localities include both caves and open camp sites. The Aurignac Cave was probably a family or tribal burial place. Near the entrance were found ashes and burnt bones of now extinct animals. Within the cave were seventeen human skeletons of various sizes associated with ancient art works and bones of extinct animals.

An interesting feature concerning Late Paleolithic man is the fact that many caves which he occupied have their walls decorated with

drawings and even pictures in colors—veritable art galleries. One of the finest examples is the Altamira cavern in northern Spain. "As we gaze at the pictures one of the first things to impress us is the excellence

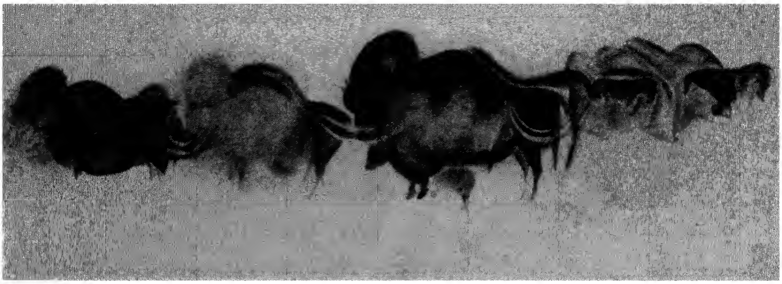


FIG. 357. The "Procession of Mammoths"; a painting by Paleolithic man in a cave at Font-de-Gaume in west-central France. Note the lack of perspective composition. (After Capitan and Breuil, courtesy of the American Museum of Natural History.)

of the drawing, the proportions and postures being unusually good. The grand bison and the charging boar are masterpieces in this respect (Fig. 356). The next observation may be that, in spite of this perfec-

FIG. 358. Line cut copy of a Paleolithic painting in the cave at Cogul, Spain. This is perhaps the only known attempt to portray human beings. (After Cartailhac and Breuil, courtesy of the American Museum of Natural History.)

tion of technique, there is no perspective composition—that is, no attempt to combine or group the figures (Figs. 357, 358). . . . In addition to these remarkable sketches in colors, the other walls of Altamira have numerous figures in black outline and also engravings. . . . It is

also clear that the work of many different artists is represented, covering a considerable period of time. The walls show traces of many other paintings that were erased to make way for new work" (C. Wissler).

Many other caves containing works of art have been discovered in northern Spain and in France.

The appearance of true man "was an event which in importance ranks with the advent of life upon the planet, and marks a new manifestation of creative energy upon a higher plane. There now appeared intelligence, reason, a moral nature, and a capacity for self-directed progress such as had never been before on earth" (W. H. Norton).

Neolithic Man. So far as known the Late Paleolithic passed gradually into the Neolithic or recent stone age when man was more highly developed and similar in structure to present-day man. The stone implements of Neolithic man were usually more perfectly made and often polished. Neolithic man lived for thousands of years during the earlier post-Glacial or Recent epoch, but various less civilized people of today still practise Neolithic culture. "The remains of Neolithic man are found, much as are those of the North American Indians, upon or near the surface, in burial mounds, in shell heaps (the refuse heaps of their settlements), in peat-bogs, caves, recent flood-plain deposits, and in the beds of lakes near shore where they sometimes built their dwellings upon piles. . . . Neolithic man in Europe had learned to make pottery, to spin and weave linen, to hew timber, and build boats, and to grow wheat and barley. The dog, horse, ox, sheep, goat, and hog had been domesticated."[1] Neolithic culture spread over most of Europe, and it gradually passed into the (present) historic age. This culture may be said to have marked the beginning of true civilization approximately 20,000 years ago.

Antiquity of Man in North America. There is no well-proved evidence for man's existence in North America earlier than very Late Pleistocene time. "The association of man in America with certain fossil forms is unquestioned, and there is a growing body of evidence strongly suggesting his contemporaneity with a considerable number of mammalian types no longer living. Such contemporaneity, however, by no means indicates any remote geological antiquity for man on this continent, and there is at present almost no paleontological evidence suggesting his presence here at a time earlier than that of the withdrawal of the last Pleistocene ice sheet" (A. S. Romer, 1935).

[1] W. H. Norton: *Elements of Geology,* p. 448.

Among the most interesting discoveries in North America were the finding of what are claimed to be human (stone) implements, associated with remains of extinct animals (presumably Late Pleistocene), near Vero and Melbourne, Florida; Folsom, New Mexico; Colorado, Texas; Fort Collins, Colorado; and Frederick, Oklahoma. In Florida human remains, with charcoal and pottery fragments, are associated with those of extinct animals, including two species of elephants. At the Folsom locality many rough, stone arrowheads or spearheads were found well below the surface associated with the bones of an extinct species of bison. Folsom-type implements, together with bones of extinct animals, have been found in various parts of the southwestern United States. In all of these cases it is a problem as to whether man lived in Late Pleistocene time, or that the associated remains of now extinct animals represent forms which lived on into post-Pleistocene time.

As late as 1931 a human skeleton was unearthed from glacial lake clays in Minnesota. The skull, plainly belonging to *Homo sapiens,* has extra-large teeth and distinct mongolian affinities. The undisturbed clay bedding shows that the person died while the lake existed in front of the waning ice sheet, some 15,000 to 20,000 years ago.

Concluding Statements. "Man, in respect to the high development of his brain and other characters, may well represent an early stage in the differentiation of a virtually new class of vertebrates. The paleontological record shows repeatedly that, in the long past, once a new class gets started, it runs for hundreds of millions of years. . . . In view of the nearly world-wide distribution of *Homo sapiens,* it would be hard to imagine any purely terrestrial epidemic or insect scourge that could wipe him out over his entire range. . . . Mankind should be a 'good risk' for survival for an indefinite period" (W. K. Gregory).

Charles R. Darwin, referring to the great doctrine of organic evolution in the last sentence of his "Origin of Species," says: "There is grandeur in this view of life with its several powers having been originally breathed by the Creator into a few forms or one; and that, while this planet has gone circling on according to the fixed law of gravity, from so simple a beginning, endless forms most beautiful and most wonderful have been, and are being, evolved."

"Man is linked to the past through the system of life, of which he is the last, the completing creation. But, unlike other species of that closing system of the past, he, through his spiritual nature, is more intimately connected with the opening future" (J. D. Dana).

APPENDIX A

OUTLINE CLASSIFICATIONS OF PLANTS AND ANIMALS

General Statement

Since a knowledge of the classifications of animals and plants and the principal characteristics of the more important groups of organisms is a fundamental consideration in the study of the life of each period, and in understanding the bearings of these life records upon the great doctrine of organic evolution, outline classifications of plants and animals, with simple explanations, are here given. The classifications are necessarily very brief, and no great degree of biologic refinement is intended. Rather the purpose is to have a convenient arrangement, essentially in biologic order, of the principal groups of organisms, commonly occurring as fossils, to form a simple basis for the discussion of the life of each period of geologic history as presented in this textbook.

Organisms are divided into many groups, such as kingdoms (e.g. plant and animal), subkingdoms, branches, classes, orders, genera, and species. A species is "the smallest group of plants or animals having certain characters in common that make them different from all other plants or animals" (G. W. Hunter). Species are grouped together into larger subdivisions called genera (singular "genus"), etc. The scientific name of an organism generally consists of two words—the first signifying the genus and the second the species, as, for instance, "Archeopteryx macrura," which literally means "primitive winged creature with a long tail," and is the name of the earth's first known bird.

PLANTS

- I. Seedless Plants
  - 1. Thallophytes (e.g. algæ and fungi)
  - 2. Bryophytes (e.g. mosses and liverworts).
  - 3. Pteridophytes
    - 1. Filicales (e.g. ferns).
    - 2. Arthrophytes (e.g. horsetail rushes).
    - 3. Lepidophytes (e.g. club mosses).

II. Seed Plants (Spermatophytes)	1. Gymnosperms (Flowerless)	1. Pteridosperms ("seed ferns").
		2. Cordaites.
		3. Cycads (e.g. "sago palms").
		4. Conifers (e.g. pines, spruces, and sequoias).
	2. Angiosperms (Flowering)	1. Monocotyledons (e.g. grasses, grains, palms, and lilies).
		2. Dicotyledons (e.g. most hard-wood trees, bushes, herbs, and familiar open-flowering plants)

I. In Seedless Plants the reproductive organs are single cells called spores.

1. **Thallophytes** show "no definite axis of upward growth, and no distinction of root, stem, and leaf. They consist of cellular tissue, being entirely destitute of wood" (J. D. Dana). In general there are two groups of thallophytes—algae and fungi—the former containing chlorophyll and able to live upon inorganic substances, while the latter are without chlorophyll and live upon organic matter. They consist of single cells or loose groupings of cells. Common examples are sea weeds, diatoms, mushrooms, and bacteria.

2. **Bryophytes** are like thallophytes in being woodless, but they develop a sort of axis of upward growth and possess leafy stems. They reproduce by spores which must develop in water. They include mosses and liverworts.

3. **Pteridophytes** comprise those seedless plants which have a clear distinction of root, leaf, and stem, the stem possessing woody fibres. (1) *Filicales* reproduce by spores which grow on the under sides of leaves. These plants have been much more favorable for fossilization than most of the foregoing, and they assume some importance in the fossil forests, especially of the great Coal Age (Pennsylvanian) (Fig. 112). (2) *Arthrophytes* have erect growth, hollow or pithy jointed stems, and leaves arranged in whorls around the stems (Fig. 113). Modern examples are the "horsetails" which are rushlike plants often seen along our streams. The ancient calamites grew to be tall trees during the Pennsylvanian period. They reproduced by spores which grew in conelike aggregations at the tops of the stems. (3) *Lepidophytes* usually have branching, non-jointed stems upon which are crowded numerous, small, single-nerved, needle-like leaves. The spores grew at the ends of the stems. Modern representatives are the small so-called "ground pines" or "club mosses" so familiar as Christmas

decorations. They are not important today, but they grew in great profusion during later Paleozoic time.

II. The SEED PLANTS comprise all those which reproduce by means of seeds.

1. **Gymnosperms,** or so-called naked seed plants, include all those which do not have their seed inclosed in a case or ovary, and their mode of growth is exogenous.[1] (1) *Pteridosperms* ("seed ferns") are fernlike plants (Fig. 116) which recently have been recognized as a group intermediate between certain seedless plants and certain seed plants. They have long since become extinct, but from the fossil and evolutionary standpoints they are important. They possessed seeds without embryo plants in them, and they showed certain features intermediate between ferns and cycads. (2) *Cordaites* (Fig. 117) are now entirely extinct, but during later Paleozoic time they grew extensively as tall, slender trees "with trunks rising to great height before branching, and bearing at the top a dense crown, composed of branches of various orders, on which simple (strap-shaped) leaves of large size were produced in abundance" (D. H. Scott). The seeds were arranged in loose clusters, not cone-shaped. (3) *Cycads* are palmlike in appearance (Fig. 182), certain of them being wrongly called "sago palms." They evolved from seed ferns. Cycad seeds are arranged in loose cone-like forms. Cycads are now not common, but they grew in profusion during Mesozoic time. (4) *Conifers* include the familiar pines, spruces, sequoias, etc. Their seeds are arranged in distinct cones. They are usually evergreens with needle-shaped leaves. They evolved from the cordaites. Both cycads and conifers possess primitive types of flowers.

2. **Angiosperms** all have their seeds inclosed in a case or ovary, and they possess true flowers and greater complexity of structure than the gymnosperms. (1) *Monocotyledons,* such as the familiar palms, grasses, lilies, etc., produce only a single leaf from the germinating seed, are endogenous, and usually have parallel-veined, simple leaves. (2) *Dicotyledons*, such as oaks, roses, and all of the familiar open-flowering plants, produce two leaves from the embryo, are exogenous, and usually have complicated net-veined leaves. They comprise the highest class of plants of all time. They made their first appearance during later Mesozoic time.

[1] Exogenous plants grow from without; have distinct bark, wood, and pith; and show concentric rings of growth, a new ring usually being added each year. Endogenous plants grow from within and have neither pith nor concentric rings of growth.

ANIMALS

- I. PROTOZOANS
  - 1. Foraminifers (calcareous shells).
  - 2. Radiolarians (siliceous shells).
  - 3. Forms without shells (e.g. amœba).
- II. PORIFERS (or Sponges)
- III. CŒLENTERATES
  - 1. Hydrozoans (e.g. jellyfishes, graptolites).
  - 2. Anthozoans (e.g. corals).
- IV. ECHINODERMS
  - 1. Pelmatozoans
    - 1. Cystoids.
    - 2. Blastoids.
    - 3. Crinoids (stone lilies).
  - 2. Asterozoans
    - 1. Ophiuroids (e.g. brittle-stars).
    - 2. Asteroids (e.g. common starfishes).
  - 3. Echinozoans
    - 1. Echinoids (e.g. sea urchins).
    - 2. Holothuroids (e.g. sea cucumbers).
- V. VERMES (or Worms). Not important as fossils.
- VI. MOLLUSCOIDS
  - 1. Bryozoans (e.g. sea mosses).
  - 2. Brachiopods (e.g. lamp shells).
- VII. MOLLUSKS
  - 1. Pelecypods (e.g. oysters, clams).
  - 2. Gastropods (e.g. snails).
  - 3. Cephalopods
    - 1. Tetrabranchs (e.g. ammonites, nautilus).
    - 2. Dibranchs (e.g. squids, cuttlefishes).
- VIII. ARTHROPODS
  - 1. Crustaceans
    - 1. Trilobites.
    - 2. Eucrustaceans (e.g. crabs, lobsters).
  - 2. Arachnids (e.g. spiders, scorpions, eurypterids, horseshoe crabs).
  - 3. Myriapods (e.g. centipedes).
  - 4. Insects (e.g. grasshoppers, flies).
- IX. VERTEBRATES
  - 1. Ostracoderms (e.g. armor fishes).
  - 2. Fishes.
  - 3. Amphibians (e.g. frogs, salamanders).
  - 4. Reptiles (lizards, snakes).
  - 5. Birds.
  - 6. Mammals (e.g. dog, man).

I. PROTOZOANS are the simplest of all animals. They consist of single cells of protoplasm and are without distinct organs. A common

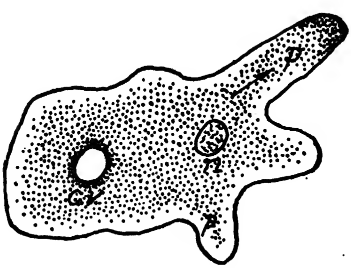


FIG. 359. A protozoan (amœba) without a shell. Greatly enlarged. (From Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company.)

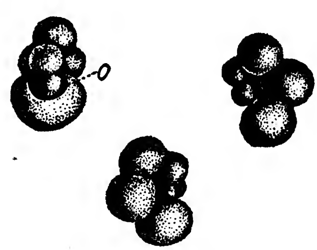


FIG. 360. Shelled protozoans (foraminifers). (From Shimer's "Introduction to the Study of Fossils," courtesy of The Macmillan Company.)

kind with no shell is the amœba (Fig. 359). The *foraminifers* have carbonate of lime shells and the *radiolarians* shells of silica. Though very small, these shells have frequently built up limestone (chalk), or chert beds. Protozoans are aquatic.

II. PORIFERS or SPONGES, which are the simplest of the many-celled animals, are saclike forms supplied with numerous pores or canals through which water containing food circulates to feed the cells. Distinct organs are lacking. Most sponges have either siliceous or calcereous skeletons. Sponges are aquatic.

FIG. 361. Sponges on a shell. (Courtesy of the American Museum of Natural History.)

III. CŒLENTERATES are also very simple, many-celled, aquatic animals, but they possess distinct mouth, body (or stomach) cavity, and usually have radiating tentacles surrounding the mouth. The canal system of the sponges is absent. *Hydrozoans* are little creatures consisting of tubelike sacs with mouth at one end surrounded by tentacles. *Anthozoans* are very much the same, but have a more or less distinct esophagus, and have the body cavity divided by radiating vertical partitions. Some hydrozoans and anthozoans colonize and some do not. Among the former, the *graptolites* (now extinct) are numerous and important in early Paleozoic rocks, while the latter or *corals* have always been prominent since rather early Paleozoic time.

IV. ECHINODERMS possess a distinct body cavity which contains the digestive or alimentary canal, distinct nervous system, and a water circu-

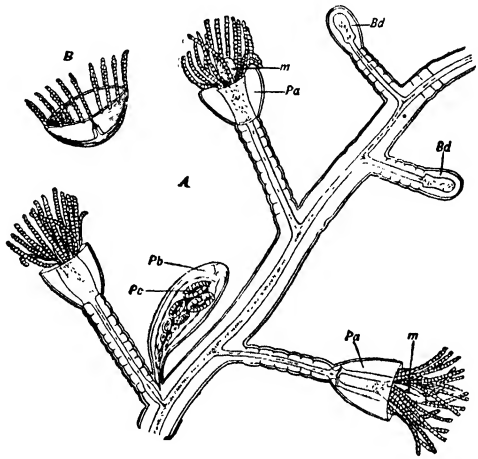


FIG. 362. Modern hydrozoans. Part of a colony much enlarged. (From Schuchert's "Historical Geology," permission of John Wiley and Sons.)

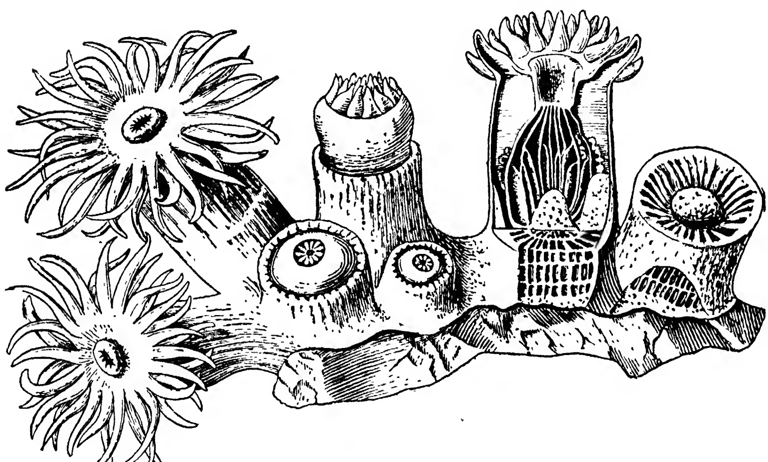


FIG. 363. A group of modern corals showing the internal structure of one individual. (After Pfurtscheller, from Schuchert's "Historical Geology," permission of John Wiley and Sons.)

latory system. Most echinoderms are radially segmented and protected by shells, but they vary greatly in size and shape. They are marine animals. 1. *Pelmatozoans* are characterized by having segmented stems

by which they are attached to the sea-floor or some object during at least part of their existence. Among pelmatozoans, the *cystoids* are

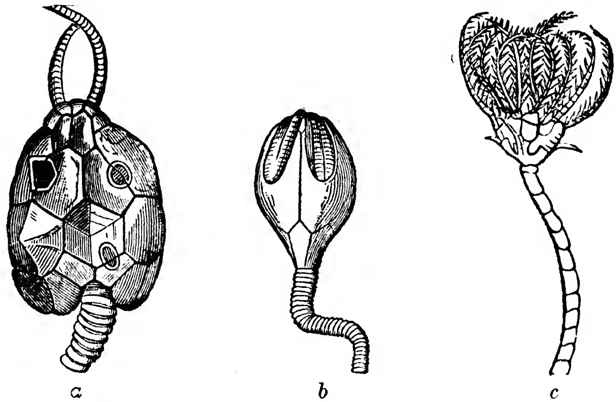


FIG. 364. Stemmed echinoderms (pelmatozoans). *a*, cystoid, *b*, blastoid, *c*, crinoid.

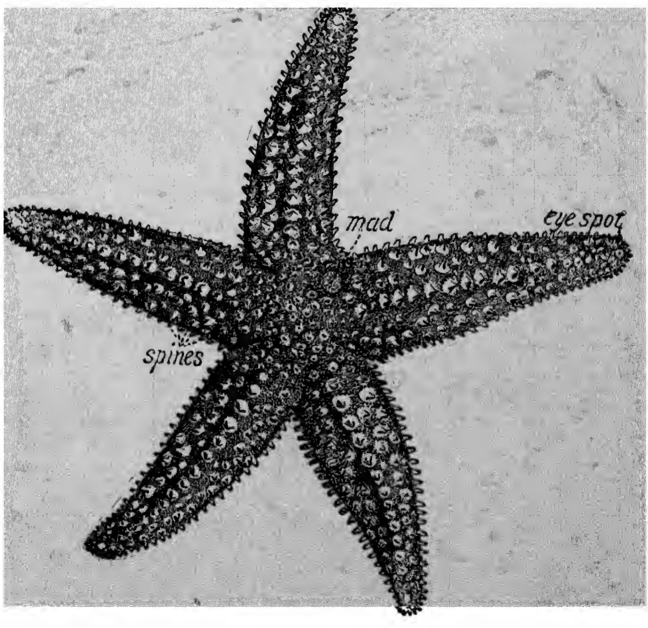


FIG. 365. A modern asterozoan ("starfish"). (From Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company.)

small, bladder-like forms with irregular radial arrangement of plates of the shell and arms wholly absent or only slightly developed; the

blastoids are budlike forms with plates of the shell in very regular radial order, and without arms; and the *crinoids* are lily-like forms with regular radial arrangement of plates of the shell, and with long, feathery arms surrounding the mouth. 2. *Asterozoans* are the free-moving, star-

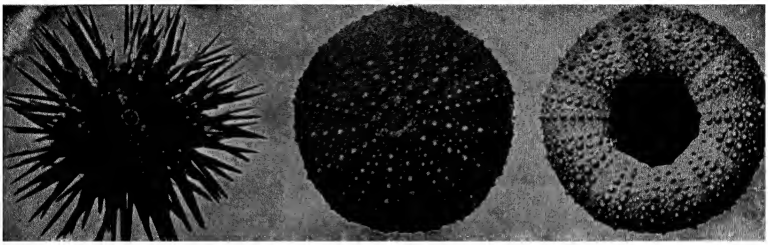


FIG. 366. Modern echinoids ("sea-urchins"), one with spines in position. (After Coe, from Schuchert's "Historical Geology," permission of John Wiley and Sons.)

shaped echinoderms usually with five arms or rays radiating from a central disk. Of these the *ophiuroids* (brittle-stars) have slender, flexible rays very distinct from the central disk, while the *asteroids* have thicker rays not so sharply separated from the central disk, and the alimentary

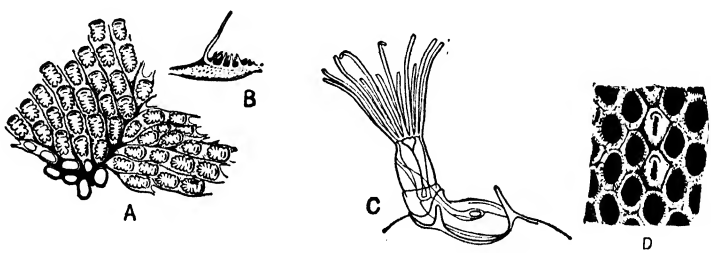


FIG. 367. Bryozoans: *A*, portion of modern colony seen from above (x15); *C*, an individual expanded; *D*, fossil form. *A-C* after Verrill and Smith; *D*, from Ulrich. (From Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company.)

canal extends into the rays. 3. *Echinozoans* are not free-moving, are without free arms, and are stemless. Of these the *echinoids* (sea urchins) have hard shells made up of calcareous plates usually immovably joined and covered with numerous movable spines; and the *holothu-*

roids (sea-cucumbers) are soft bodied, with leathery covering, tentacles around the mouth, and skeletons of scattering limy spicules.

V. Vermes or Worms include a large group of forms more complex in organization than the preceding groups. Some are segmented and others are not. Since hard parts are very rarely developed, the worms are of no great importance as fossils, their presence usually being indicated by trails, burrows, or tubes made in mud or sand.

VI. Molluscoids, as the name suggests, bear a resemblance to the mollusks. They differ from the anthozoans, echinoderms, worms, and arthropods in the entire absence of body segmentation. Absence of distinct head and foot, the lower development of the nervous system, and usual lack of locomotive power distinguish them from mollusks. A highly characteristic feature of the molluscoids is a sort of collar or ridge, bearing fringe-like tentacles around the mouth. The soft parts of the animal are protected by a limy or chitinous covering. 1. *Bryozoans* form tiny mosslike tufts which nearly always colonize and suggest the anthozoans in outward appearance, though they are much more highly organized. With few exceptions the bryozoans secrete calcareous coral-like skeletons. 2. *Brachiopods* have two shells (valves)—top and bottom—enclosing the soft body of the animal which contains two long, limy,

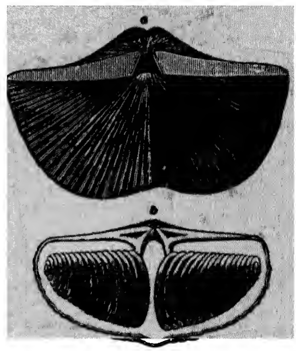


Fig. 368. Brachiopod shells (fossil forms). The lower one shows internal spiral supports.

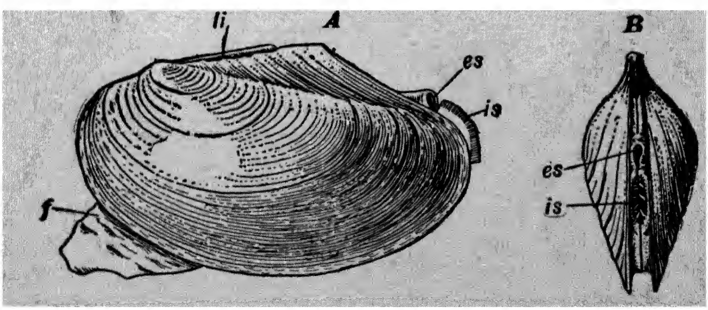


Fig. 369. A modern pelecypod. *A*, side view; *B*, end view. (After Howes, from Schuchert's "Historical Geology," permission of John Wiley and Sons.)

variously shaped, sometimes coiled, supports. In fossil form the brachiopods are most readily distinguished from certain mollusks (pelecypods),

which are also bivalves, by the bilateral symmetry of the shells. That is, a plane of symmetry may be passed through the valves at right angles to the hinge line. Bryozoans and brachiopods are both very abundant as fossils, especially in the older rocks.

VII. Mollusks, like molluscoids, lack segmentation, but they are more highly organized with more or less distinctly developed body and locomotive organs. Both aquatic and land forms are common. They can crawl, swim, or burrow. Nearly all have shells (generally external), and gills for respiration. 1. *Pelecypods* (e.g. oysters and clams) are supplied with two external shells—right and left—nearly alike and hence they are bivalves, but they differ from brachiopods (also bivalves) in the absence of bilateral symmetry. The head is less distinct than in the other mollusks. 2. *Gastropods* (e.g. snails) have distinct head with eyes and one or two pairs of tentacles, and they are almost invariably covered by a one-chambered shell. 3. *Cephalopods* have well-defined foot; head armed with tentacles; and large complex eyes. They propel themselves rapidly by forcible ejection of water. *Tetrabranchs* (e.g. modern pearly nautilus) are the so-called chambered cephalopods because the external shell, straight or coiled, is divided into compartments. They are four-gilled and with numerous tentacles. *Dibranchs* (e.g. so-called cuttlefishes) are two-gilled; with either eight or ten tentacles; bag for secreting an inky fluid; and almost invariably without external shell. Usually there is a sort of cigar-shaped internal shell. Mollusks of all classes have been abundantly preserved in rocks of all but the earliest geologic ages.

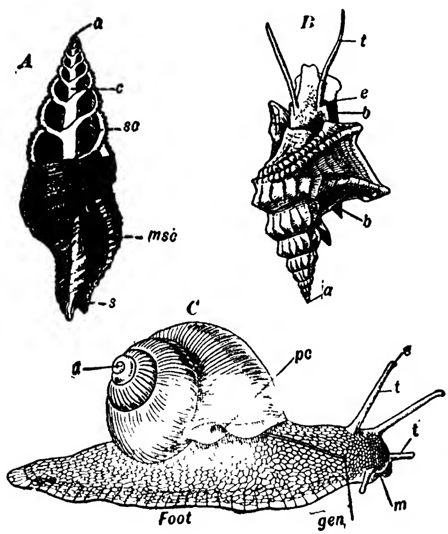


FIG. 370. Gastropods. *A* and *B*, marine forms; *C*, land snail. (From Schuchert's "Historical Geology," permission of John Wiley and Sons.)

VIII. Arthropods are highly characterized by longitudinal body segmentation; jointed appendages (usually a pair from each segment);

and usually by a pair of nerve centers in each segment. 1. *Crustaceans* (e.g. lobsters and crabs) are water animals breathing by means of gills or through the body; usually with two pairs of well-developed antennæ (feelers); and covered with a chitinous or calcareous crust or shell. The Paleozoic trilobites were low-order crustaceans. 2. *Arachnids* (e.g. spiders and scorpions) have a head-thorax portion with six pairs of appendages and an abdominal portion usually with no appendages. They have no antennæ. They are mostly land arthropods breathing by means of air sacs, and with four pairs of legs. Aquatic forms are represented by horseshoe crabs and Paleozoic eurypterids. 3. *Myriapods* (e.g. centipedes) are land arthropods with numerous legs; one pair of antennæ; and no wings. 4. *Insects* (e.g. grasshoppers and butterflies) are also land arthropods with one pair of antennæ, but with three pairs of legs, and nearly always with wings.

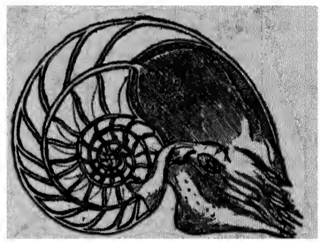


FIG. 371. A modern chamber-shelled cephalopod (Nautilus) showing the internal shell structure.

IX. VERTEBRATES are eminently characterized by the possession of a vertebral column, which, in all but the very low forms, is a thoroughly ossified backbone. Vertebrates include the highest known of all animals. 1. *Ostracoderms* (e.g. armor fishes, now wholly extinct) are among the very simplest of vertebrates (see Fig. 134). They are of particular interest from the standpoint of the evolution of the fishes and higher vertebrates. Characteristic features are given above in connection with the life of the Devonian period. 2. *Fishes* always live in water; have distinct cartilaginous or bony vertebral column; distinct jaws; pairs of fins; and gills. Subclasses are described in Chapter XVI. 3. *Amphibians* (e.g. frogs and salamanders) live either in water or on land. In the early stage of development of

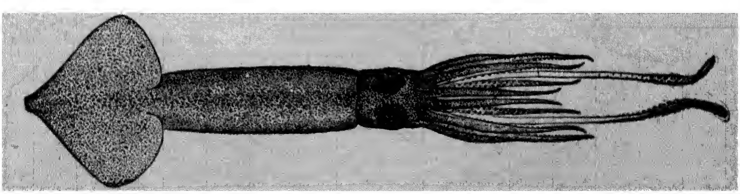


FIG. 372. A modern squid. (After J. H. Blake, from Shimer's "Introduction to the Study of Fossils," permission of The Macmillan Company.)

the individual (e.g. tadpole stage), they are aquatic, and breathe by gills, while in the adult stage they breathe by lungs and are largely terrestrial in habit. They never have fins. 4. *Reptiles* (e.g. snakes and crocodiles), though in many ways like amphibians, never have gills, and always have scales or bony plates developed from the skin. They are the most highly organized cold-blooded animals. 5. *Birds* are plainly distinguished from all other animals by their covering of feathers. They are too familiar to need special description. They are warm-blooded creatures with well-developed heart and circulation of blood. 6. *Mammals* (e.g. dog and man) include the highest of all organisms, a characteristic being that they all suckle the young. They are mostly quadrupeds, covered with hair, and dwellers on land. The whale is an exceptional mammal.

Vertebrate fossils are common and of special interest because they show the development of the higher animals. The simplest (ostracoderms) have been found in rocks of Ordovician age (see above), and higher and higher forms were gradually introduced and developed until the most complex mammals appeared in comparatively recent time.

APPENDIX B

ORGANIC EVOLUTION[1]

Definition

Organic evolution may be defined as orderly change among organisms, both plants and animals. It "means that the present is the child of the past and the parent of the future" (J. A. Thomson).

Evidences of Evolution

Geological Evidence. One of the plainest and most important lessons taught in this book is that, as the hundreds of millions of years of geological time passed, both plants and animals, starting from low-order forms, generally became biologically more complex in structure. Not all changes in the history of living things have been progressive. In some cases there have been setbacks or retrogressions among groups of organisms. The great, general changes in evolution have, however, been progressive, bringing into existence a succession of higher (or more complex) plants and animals in almost, if not quite, the order of geological time, as clearly shown in the table in Chapter V. Man, the most complex of all known organisms, appeared in very late geological time.

More in detail, various classes and smaller groups of animals furnish remarkable illustrations of change through longer or shorter parts of geological history. Mention may be made of the chambered cephalopods (Cambrian to present), insects (Pennsylvanian to present), fishes (Silurian to present), placental mammals (Cretaceous to present), and man (Quaternary). Thus there is overwhelming evidence of evolution in the geological record. Just what evolutionary changes the future will witness we do not know, but we are quite certain that creation is not a finished act.

[1] The reader who may wish to go more fully into this subject will find an authoritative, popular account called "The Story of Evolution" in Thomson's "The Outline of Science."

Anatomical Evidence. "There is also anatomical evidence of a most convincing quality. In the forelimbs of backboned animals, say, the paddle of a turtle, the wing of a bird, the flipper of a whale, the foreleg of a horse, and the arm of a man, the same essential bones and muscles are used to such diverse results" (J. A. Thomson). Again, the primates, including lemurs, monkeys, apes, and man, all have skeletons built on the same plan almost bone for bone. Not only the bones, but also many of the body organs are essentially the same. A great many other examples of similarity of structure in allied groups of animals could be mentioned. Such remarkable similarities certainly indicate kinship of animals within the groups.

Embryological Evidence. Still other convincing evidence of organic evolution is found in the life histories of individuals. It is a law of life that every individual, including the human being, begins as a single cell and passes through a series of changes before reaching a full-grown condition. Thus the frog (an amphibian) lays eggs in water. The tadpoles hatched from the eggs are distinctly fishlike with gills and tails, but without legs. In time the gills and tails disappear, lungs and legs are formed, and the creature can live on land. It is plain, from the geological record, that amphibians not only appeared later than fishes, but also that they evolved from the fishes. Such a brief repetition of various features of a race or group in the life history of the individual is called the *law of recapitulation*. It is more or less true of nearly all organisms. Even in man's pre-natal history the embryo is, in its early stages, remarkably similar to the embryos of such diverse forms as frog, chicken, and dog. Here again we have striking proof of the remarkable kinships of large groups of animals.

Factors of Evolution

We should not be led astray by those who refuse to accept evolution as a fact because its exact cause is not known. It would be just as logical to assert that there was no Quaternary Ice Age because we do not know precisely what caused it. In the scientific world the *fact* of evolution is certain—evolution is a law of nature—but the *factors* or *causes* of evolution are by no means well understood. Some of the most commonly suggested factors are the following:

Heritable Variations. It is well-known that the offspring is essentially like the parent, but it is also true that no two animals of the

same species, however closely related, are precisely alike. Marked "heritable novelties or variations often crop up in living creatures, and these form the raw material of evolution. These variations are the outcome of changes in the germ cells that develop into organisms" (J. A. Thomson). Just how such germ-cell changes occur is not positively known, but they are probably controlled by the so-called *genes* which are tiny particles in the germ cells. Through hereditary tendency a marked variation may become more or less established or fixed in a line of descendants.

Natural Selection. In the world of living things remarkably few seeds or germ cells ever develop into individual plants or animals, and, of the individuals produced, an amazing number die when young. Diseases, lack of food, and extreme temperatures exact heavy tolls. Competition among plants and animals is more or less severe—often very severe. Only those survive which are well adjusted to the conditions under which they live. Such a natural process, involving "survival of the fittest," is known as *natural selection.* By such a struggle for existence nature gets rid of the unfit, and leaves the fit to live and reproduce. Because of the tendency toward variation in a species, an occasional individual may appear with some new feature which enables it to face the competition for existence better than the other individuals of the same species. When such a variation is heritable, a new and better breed of plant or animal results. Animal and plant breeders watch for such variations, and, by proper artificial selection and mating, they have produced remarkable changes among plants and animals.

Influence of Environment. As pointed out in numerous places in the pages of this book, the earth's surface has undergone a very great number of changes at many times and in many regions. Some of these changes were small, but others were profound, affecting large parts of continents. The coming and going of mountains, the advances and retreats of the seas, the spread of vast ice sheets, times of extensive volcanic activity, and many other physical changes, often produced important changes in the habitats of living things, involving alterations in climatic conditions and food supply. Animals and plants have been forced to adapt themselves to the new conditions or become extinct. The record of the rocks shows that race after race failed in the struggle, while others went on, steadily advancing in complexity of structure or adaptability to changing environments as the ages rolled by. It is prob-

ably true that not a species of plant or animal from the Paleozoic era has survived to the present day, and very few from the Mesozoic era.

Some of the most profound evolutionary changes among organisms accompanied the tremendous physical changes at the end of the Paleozoic and Mesozoic eras. The increasing cold of later Cenozoic time, reaching a climax during the Ice Age, also marked a time of great evolutionary changes.

Evolution of Man

The following statement, issued in 1926 by the Council of the American Anthropological Association, clearly shows the position of the modern scientific world in regard to organic evolution, particularly with reference to man:

"In view of the dogmatic objections raised against the theory of evolution the Council of the American Anthropological Association have thought it advisable to formulate the present position of scientific inquiry.

"The plants and animals belonging to early periods of the earth's history show that the forms have not remained the same for any length of time. The changes that have occurred are of such character that we are compelled to consider the later forms as descendants of older forms. No form of living being has remained the same through the ages. The evidence of past times is corroborated by the structural and developmental analogies observed in related forms, proofs of a gradual differentiation from common ancestral forms.

"The minute structure of all living matter is alike and shows that all organisms, from the lowest to the highest, must be considered as a unit.

"Man has succeeded in producing a variety of forms of domestic animals and cultivated plants which differ from their ancestors. Our success, accomplished in a very short period, indicates that in long periods nature will produce more fundamental changes.

"Man is part of the animal world. In all respects his anatomical structure conforms to that of the rest of the animal world. His prenatal life closely parallels that of the higher mammals. The same influences that control their development after birth control him and he responds in a like manner to the environment in which he is placed. Prehistoric archeology has shown that, in the course of the ages, man has undergone great changes in physical type and that ancient man differed from modern races, the more so the more ancient the remains.

"Local types of man have developed on every continent and their existence proves that changes in the heritable characteristics of racial groups are effected in the course of time.

"We must conclude that the bodily form of man as well as that of animals and plants has changed and is still changing, not in the course of centuries, but in longer periods.

"The exact cause of changes in the form of organisms and the conditions under which they occur, as well as the causes making for stability, are still imperfectly known. The principle of change has been so well established that it should become the common property of mankind."

APPENDIX C

Selected General References

Dana: *Manual of Geology,* Part 4 (American Book Co., 1895). A very elaborate older American work.

Chamberlin and Salisbury: *Geology,* Vols. 2 and 3 (Henry Holt and Co., 1906). A very elaborate American work.

Chamberlin and Salisbury: *College Geology,* Part 2 (Henry Holt and Co., 1909). A briefer discussion than in the larger work of these authors. Revised by R. Chamberlin and P. McClintock, 1930.

Geikie: *Textbook of Geology,* Vol. 2 (Macmillan Co., 1903). A comprehensive English work with emphasis upon European geology.

Kayser: *Lehrbuch der Geologie,* Part 2 (F. Enke, Stuttgart, 1912). A comprehensive German work with emphasis upon European geology.

Schaffer: *Lehrbuch der Geologie,* Part 2 (F. Deuticke, Leipsic, 1924). A comprehensive work in German with European emphasis (largely paleontological).

Haug: *Traité de Géologie,* Vol. 2 (A. Colin, Paris, 1911). A comprehensive French work with emphasis upon European geology.

Willis and Salisbury: *Outlines of Geologic History with Especial Reference to North America* (University of Chicago Press, 1910). Not a textbook, but contains important general papers by various American geologists.

Blackwelder: *Regional Geology of the United States of North America* (Stechert & Co., 1912). Contains brief outlines of the stratigraphy and geologic history of the United States.

Le Conte: *Elements of Geology,* Part 3 (Appleton and Co.). An older fairly comprehensive treatment of historical geology with special reference to North America. Revised by H. L. Fairchild, 1903.

Scott: *An Introduction to Geology,* Vol. 2, third edition (Macmillan Co., 1932). A fairly comprehensive discussion of earth history.

Pirsson and Schuchert: *Textbook of Geology,* Part 2 (John Wiley & Sons, 1915, 1924). A comprehensive treatment of historical geology. Fourth edition by Schuchert and Dunbar, 1941.

Moore: *Historical Geology* (McGraw-Hill Co., 1933). A comprehensive treatment of the subject.

Cleland: *Geology, Physical and Historical,* Part 2 (American Book Co., 1916). A fairly comprehensive treatment of historical geology.

Grabau: *A Textbook in Geology,* Part 2 (D. C. Heath and Co., 1921). A comprehensive treatment of historical geology.

Shimer. *An Introduction to Earth History* (Ginn and Co., 1925). Contains a brief discussion of historical geology.

QUIRKE: *Elements of Geology,* Part 3 (Henry Holt and Co., 1925). A very brief presentation of historical geology.

BRADLEY: *The Earth and Its History* (Ginn and Co., 1928). Contains a brief presentation of historical geology.

MILLER, W. J.: *Elements of Geology* (D. Van Nostrand Co., 1931, 1939). Contains a brief discussion of historical geology.

SNIDER: *Earth History* (Century Co., 1932). A fairly comprehensive discussion with emphasis upon paleontology.

EMMONS, THIEL, STAUFFER, AND ALLISON: *Geology* (McGraw-Hill Co., 1932). Contains an elementary discussion of historical geology.

BRANSON AND TARR: *Introduction to Geology* (McGraw-Hill Co., 1935). Contains a brief discussion of historical geology.

MILLER, W. J.: *The Story of Our Earth* (Vol. 3 of Popular Science Library by P. F. Collier and Son Co., 1922, 1940). Contains an elementary account of historical geology in popular form.

SCHUCHERT AND LE VERNE: *The Earth and Its Rhythms* (Appleton and Co., 1927). Contains an elementary account in popular form.

INDEX